W. P. Wood

TRANSACTIONS

of the American Society for Steel Treating

FEATURES

Test Methods for Determining the Machinability of Metals —*O. W. Boston* 659

Hot Aqueous Solutions for Quenching Steels —*H. J. French and T. E. Hamill* 711

Brittle Range in 18 and 8 Chromium-Nickel Iron —*H. H. Lester* 743

Nondestructive Testing —*Elmer A. Sperry* 771

Engineering Index 799

Vol. XVI No. 6
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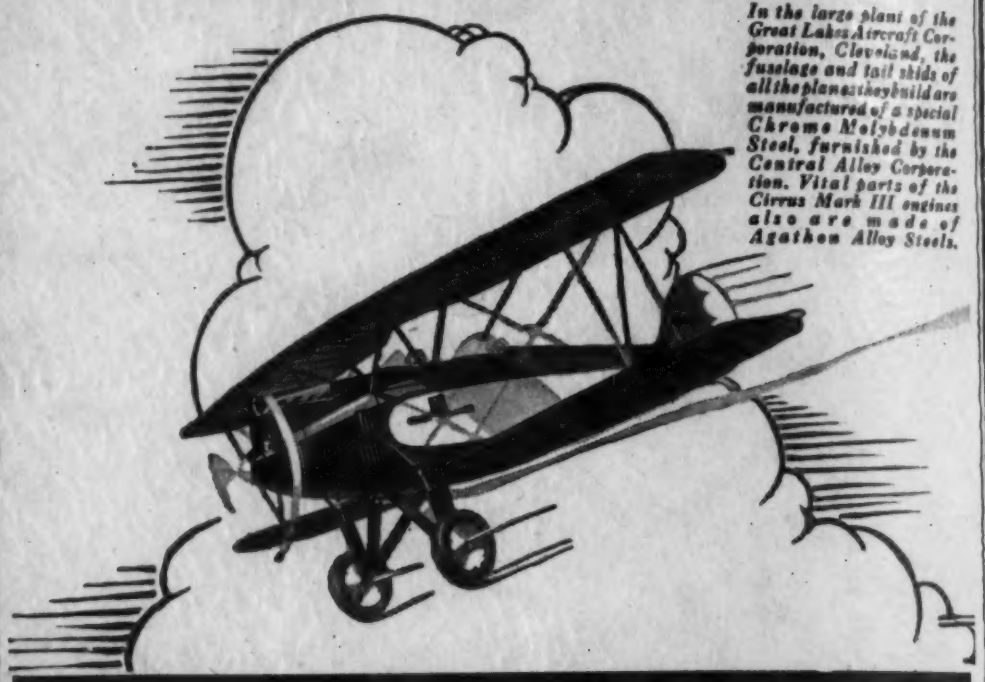

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TRANSACTIONS
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METHODS OF TESTS FOR DETERMINING THE MACHINABILITY OF METALS IN GENERAL, WITH RESULTS

By O. W. Boston

Abstract

The results of a series of experiments made on eighteen ferrous metals and twenty-one nonferrous metals are presented in order to indicate, if possible, the best method for determining whether or not the material is suitable for machining purposes. It is shown that the Brinell number varies almost directly with the physical properties of these metals, such as the ultimate strength in tension, compression, and shear, as well as the Rockwell hardness number. The scleroscope values, however, show an independent relation.

The machining properties as represented by the force on a planer tool, the energy required to remove a chip by milling, the torque and thrust on a drill while drilling, and the penetration of a drill under a uniform load are presented in tables and shown graphically. The force and energy curves agree quite consistently as to the cutting quality of the material. The penetration curve is a reciprocal function of the force and energy curves. The Brinell number bears little relation to the machining qualities. Values representing the power required to cut one cubic inch of metal per minute for the various metals are also given for drilling, milling, and planing.

THE object of this paper is to show results of various methods of tests on materials of a wide variety, covering both ferrous and nonferrous types, to indicate, if possible, the best method for

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determining whether or not the material is suitable for machining purposes. In a paper before this society[1], the writer gave an outline of various methods which are being used to designate the machinability of metals and, under each method of test, outlined the work by various authors as published in a few outstanding papers on the subject. As most of the work on machinability treats of a single type of test on certain metals, it was thought desirable to correlate this work by testing each of a number of metals by each method, so as to show, if possible, the difference or similarity in results.

The Tests

Each sample of material was submitted to the following tests:

1. The Brinell, Rockwell, and scleroscope hardness readings were determined as follows:

In the Brinell tests on steels a 3000-kilogram load and a 10-millimeter ball was used, but for the nonferrous materials, a 500-kilogram load was used with a 10-millimeter ball. The time of duration of the load was 30 seconds, and measurements of the impressions on a ground surface were taken with a Brinell microscope. The readings were taken across the diameter lengthwise of the bar in case of rolled stock.

The Rockwell reading for the ferrous metals was read on the B scale, using a 1/16-inch diameter ball and 100-kilogram load. For the nonferrous metals, the scale B Rockwell reading is given but a ⅛-inch ball was used with 100-kilogram load.

The scleroscope readings were obtained with a Shore scleroscope.

2. The force developed in the direction of cut by a planer tool was measured. The tool was of the end cutting type, 0.500 inches wide and provided with a 15-degree front rake but no side rake. The corners of the tool were beveled off, making a 1/64-inch flat at a 45-degree angle, to insure greater endurance of the geometric shape of the high speed steel tool. After grinding to shape and size the tool was honed. A depth of cut of 0.010 inches as measured on a dial gage was taken in all cases. An average was made of from six to twelve consecutive readings, when cutting at a speed of twenty feet per minute.

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[1] O. W. Boston, "The Machinability of Metals," Transactions, American Society for Steel Treating, Vol. 13, January, 1928, page 49.

3. The torque and thrust developed by a ¾-inch diameter high speed steel twist drill was determined. The drill had a helix angle of 30 degrees and a clearance angle of 3 degrees, 48 minutes as measured at the periphery. The web thickness at the point was 0.095 inches and the outside diameter was 0.750 inches. The drill was ground on a S. P. K. Blau drill grinder with a drill overhang from the jaws of ⅜ inches. The grinder forms the drill point so that it has a conical surface back of the cutting edge. The drill was measured on a special measuring instrument to make sure that the cutting edges were of the same length and position to cut chips of equal thickness. This drill was rotated at 153 revolutions per minute and was given a feed of 0.012 inches per revolution.

4. The drill penetration or the distance traveled by a ¼-inch diameter twist drill for 100 revolutions when rotating at 504 revolutions per minute under a dead load, including the weight of the drill and drill spindle, of 93.75 pounds, was determined. The twist drill had an outside diameter of 0.250 inches, a web thickness at the point of 0.0269 inches, and a helix angle of 24 degrees. The clearance angle was about 6 degrees and 30 minutes at the periphery. This drill was ground on a S. P. L. Blau drill grinder which formed a cylindrical surface back of the cutting edge.

5. The energy absorbed by a single tooth milling cutter of the side cutting type, that is, similar to a cutting-off tool, was determined. The tool had a width of 0.250 inches, a 15-degree front rake, but no side-rake angle, and a 4-degree clearance angle on the end and sides. The edges of the cutter were beveled to 1/64-inch flat at an angle of 45 degrees and the tool was then honed all over. The cut taken had a radius of 1¾ inches, a depth of 0.125 inches, and a feed of 0.010 inch per chip.

The influence of the material on the "tool life" under standardized conditions, as well as the relation between the material and the "finish" which may be obtained by certain cutting tools, is of real commercial value. Such tests were not included with those described above, as there was insufficient material of each type on hand to make it possible to obtain any information of value in respect to the "tool life" factor. It was deemed inadvisable to attempt to include the subject of "finish" in these tests, as there appears to be no way of correlating the finish obtained by a specific tool on one type of metal with that on another. Also, one tool shape might not

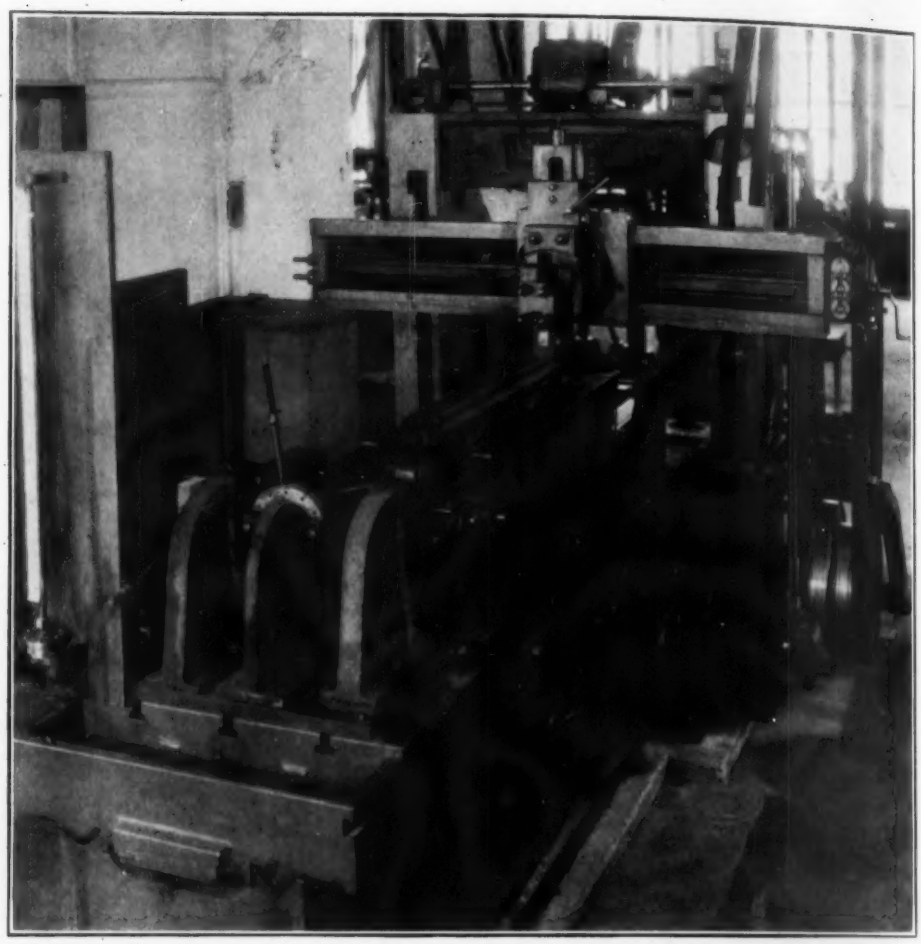


Fig. 1—Planer and Dynamometer.

give a satisfactory finish on all metals. Specific shapes must be employed to produce desirable finishes, and these may not prove suitable as to "tool life." The value of comparing the finish on one metal by one tool with that on another metal by another tool is questionable. There is undoubtedly much to be learned about the condition a material should be in to give the most desirable finish for a specific tool and cut, but only materials of a like nature should be so compared. Experiments along this line are planned for the near future.

The Testing Machines

The testing machines used in conducting the tests for machinability as outlined above may be described briefly as follows: Fig. 1

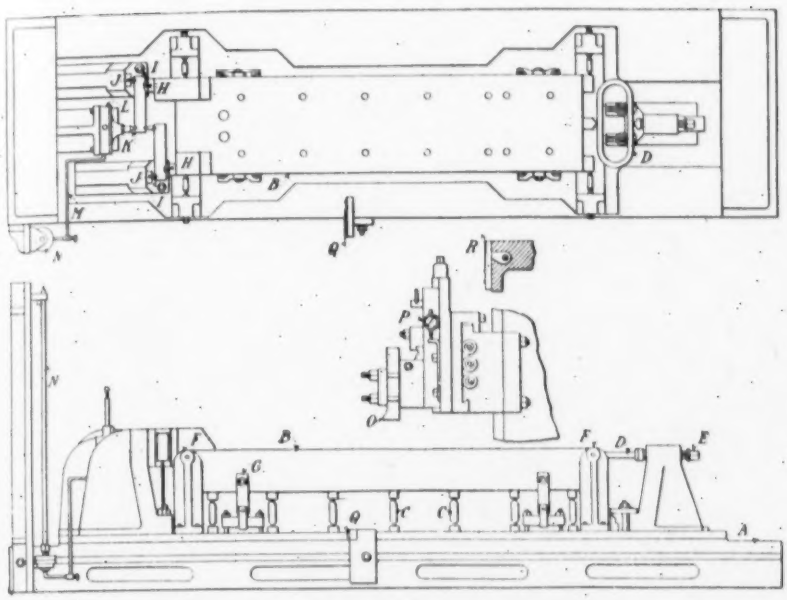


Fig. 2—Line Diagram of Planer Dynamometer.

shows the specially designed dynamometer for measuring the force on a planer tool in the direction of cut as mounted on the 30-inch by 36-inch by 8-foot planer. The power was furnished from a main drive shaft, a satisfactory arrangement in that the horsepower output of the machine was measured rather than the input. The cutting speed for all of these tests was 20 feet per minute. Fig. 2 shows a line diagram of the dynamometer which consists essentially of a cast iron bed B, weighing about 1300 pounds, mounted on seven horizontal knife edges C. The bed is prevented from moving sideways when a side-rake angle on the tool is used by the four horizontal floating pins shown in the plan view, supported by the brackets F. The bed is kept from being lifted by four knife edges shown at G. An initial load of 2,000 pounds, tending to force the bed to the left, was put on the bed by compressing the loop spring D. This load keeps the whole mechanism in compression, thereby eliminating chatter during a cut and also keeps the mercury column gage under an initial load which is indicated as a zero point on the scale. The loop spring was made of ¾-inch square spring steel having major and minor axes to center of bar of 11½ and 4¾ inches respectively. It had previously been calibrated on a universal testing machine. This spring also served for calibrating the mercury column gage N. For more detailed description of this equipment, see *Transactions*, A. S. M. E., Vol. 48, 1926, page 749. The thickness of chip for

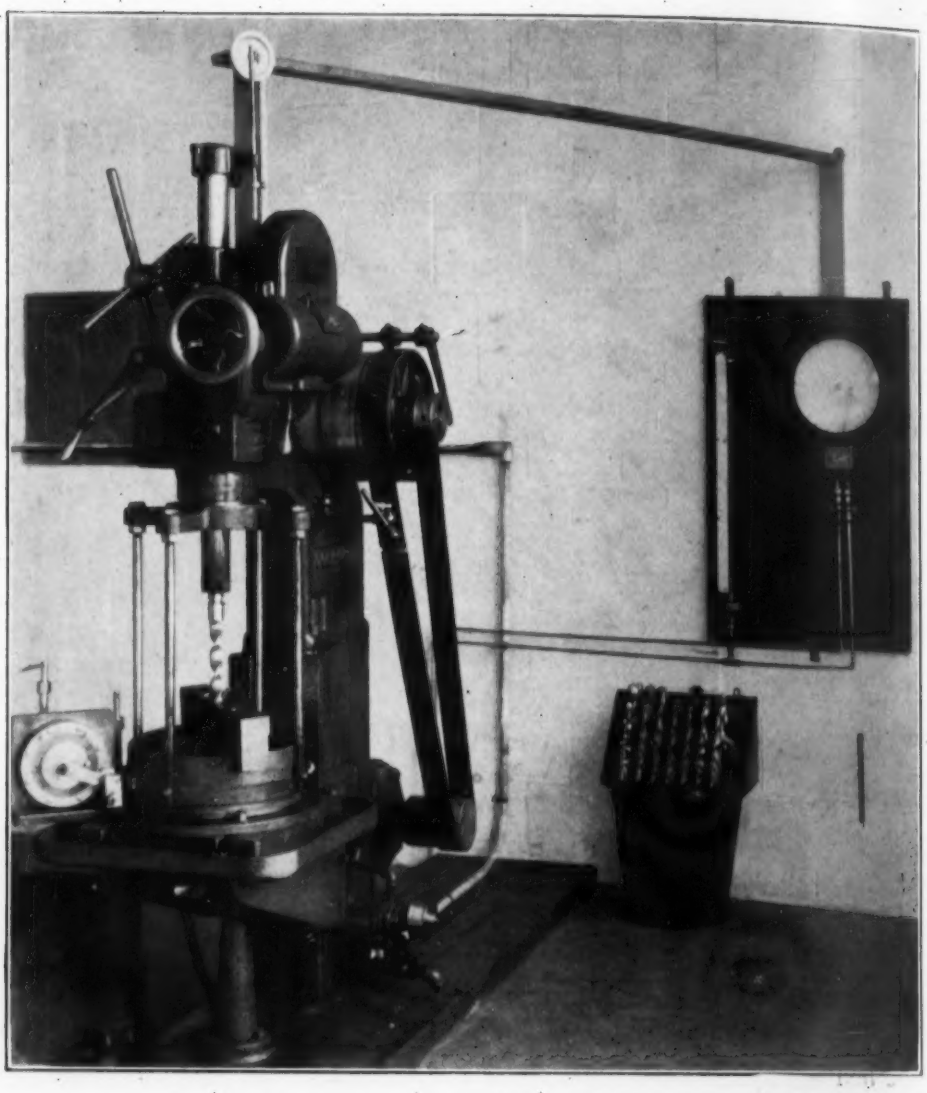


Fig. 3—Drill Press and Dynamometer.

each cut in this test was determined by lowering the head and tool vertically 0.010 inches as measured on the Ames dial indicator mounted on the right hand side of the head. Six to twelve consecutive cuts were taken on each test piece and an average determined. This eliminated even any very slight deviation from the 0.010-inch feed per cut which might occur for a single chip.

The torque and thrust developed by the ¾-inch drill were determined by means of a torque and thrust dynamometer mounted on a manufacturing-type drill press shown in Fig. 3. The press

was driven by a 5-horsepower, 220-volt, 3-phase, 60-cycle motor through a short belt. The motor was mounted directly on the press column. All tests were run without a coolant or lubricant on the drill. The thrust on the drill was measured on the recording chart of a gage shown mounted on the wall. This pressure was exerted directly on a plate bearing on a rubber diaphragm shown just above the dynamometer base. Water underneath this rubber diaphragm was compressed and the pressure was transmitted to the gage through the ⅛-inch pipe below and to the left of the gage. The plate resting on the rubber diaphragm, which carried the thrust load, was made to form the lower race of a large ball bearing consisting of sixty-four ½-inch balls, so that the table of the dynamometer was free to rotate except for the arm extending to the left, which had a bearing against a piston resting on a rubber diaphragm. The length of this arm was just one foot. The pressure on this torque rubber diaphragm compressed water back of it. This pressure was transmitted through the ⅛-inch pipe leading both to the mercury column and the gage mounted on the wall. The mercury column calibrated against the gage gave a scale reading for check purposes, somewhat larger than that obtained on the gage. The four rods leading from the table of the dynamometer to a spider fitted around the spindle housing were provided in order to prevent tilting of the dynamometer table. To eliminate friction, the bearing between this spider and the spindle housing consisted of twenty-four ½-inch balls mounted on appropriate races to permit a slight vertical adjustment of the dynamometer as a result of the thrust of the drill.

The chart of the recording gage was made to rotate to register the travel of the spindle by means of a fine wire which passed from the upper end of the spindle over pulleys to a position vertically above the gage, thence downward, making one turn about a special pulley on the shaft of the gage to the counter weight shown near the floor.

For determining the drill penetration under a given load, a sensitive drill press was remodeled so as to carry on the upper end of the rotating spindle a weight of sufficient amount to cause the tool to dig in when the spindle was rotated. By trial and error, the weight of 93.75 pounds, including the drill spindle and drill, was arrived at in order to cause a ¼-inch twist drill to cut freely. A lighter load on the spindle or a larger size drill did not seem to give satisfactory results, as the drill could not be made to bite on some of

the harder materials. This drill press was also driven through a short belt by a 5-horsepower motor, a tight and loose pulley being provided. After mounting the specimen to be tested on the drill press table or in a vise, the drill was first allowed to penetrate about ⅛-inch. By means of a beam-type indicator attached to a vernier height gage, the height of a particular point on the spindle was measured. With a speed counter attached to the spindle, the belt was next shifted from the loose to the tight pulley, causing the spindle to rotate. After 100 revolutions plus or minus, the spindle was stopped and the height of the point on the spindle was again measured. The difference in measurements gave the penetration of the drill for the actual number of revolutions shown on the speed indicator. This was then reduced to 100 revolutions per minute.

This method of measuring the drill penetration was rather tedious and required considerable time, so in some subsequent tests, the following method was used: Two beam-type indicators were mounted on a vernier height gage so that the vertical distance between the two, as measured with Johansson blocks, was just 0.250 inches. The slide on the vernier scale was so adjusted that after the drill had penetrated about ⅛-inch, the upper beam indicator bearing on the end of the drill sleeve would indicate zero, at which time a stop watch would be started. After drilling continuously until the second indicator showed zero, the stop watch was stopped. This gave the lapsed time for the drill to penetrate the ¼-inch. These results checked remarkably well with those obtained by the method outlined above. Averages of four to six or eight readings were taken for each test specimen.

All of the drill penetration tests of this paper were obtained with the same drill and with one grinding, as it was found almost impossible to regrind the drill, even on a machine, to give results comparable with those of the first grinding. After all tests were completed, many duplicate tests were run to check the influence of the dulling of the drill. It was concluded, however, that the dulling from all of the tests was insufficient to materially affect the results.

The energy absorbed by the single tooth milling cutter, side cutting (end cutting) type, was measured on the machinability tester shown in Fig. 4. This was designed by Carl Oxford and is described in detail in the *Transactions*, A. S. M. E., Vol. 43, 1921, page 549. If the pendulum be allowed to fall freely from the top vertical position it will rise almost to the same height. The freely rotating

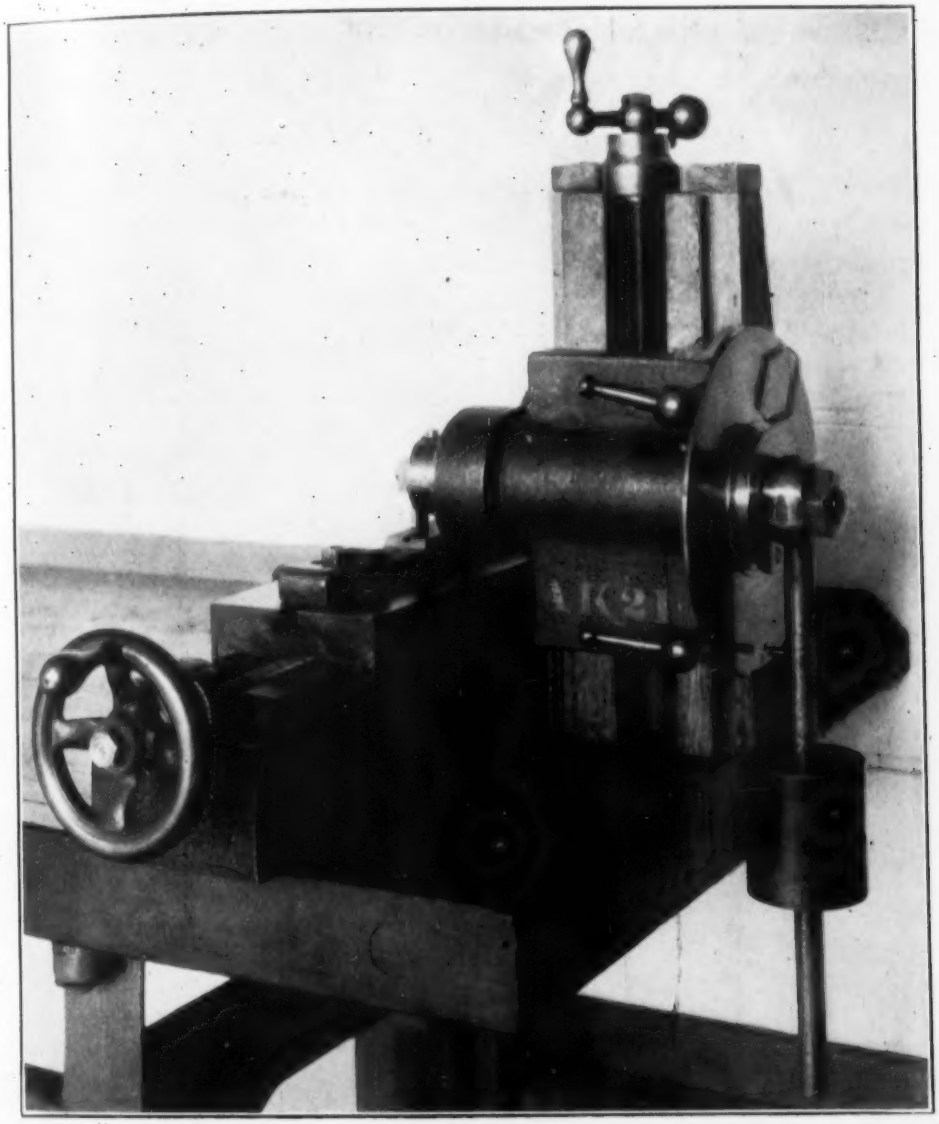


Fig. 4—Milling Dynamometer.

pointer is rotated with the pendulum and indicates on the steel disk the highest position to which the weight rises. This position is taken as the zero reading to allow for friction of the bearings. If the material is bolted to the bed and adjusted for depth of cut and feed, a subsequent fall of the pendulum will form a chip and the pendulum will not swing as high after taking the chip as when taking no chip. This change in height is a measure of the energy in foot-pounds given up in forming the chip. It is the same principle as is used in impact

Table I
Steel Machinability Test Bars
Showing Chemical Anaylsis

Bar No.	Use or Type	Chemical Analysis, Per Cent						
		C	Mn.	Si	S	P	Ni.	Cr.	Manufacturer
2	'Standard' Tool Steel.....	0.97	0.31	0.10	0.027	0.025	....	....	Columbia
11	0.15% Carbon, O. H.	0.15	0.24	0.13	0.029	0.014	....	....	Colonial
111	0.15% Carbon, O. H.	0.15	0.24	0.13	0.029	0.014	....	....	Colonial
11111	0.15% Carbon, O. H.	0.15	0.24	0.13	0.029	0.014	....	....	Colonial
28	S. A. E. 1020.....	0.21	0.27	....	0.030	0.022	....	....	Ryerson
29	S. A. E. 2345.....	0.48	0.59	....	0.024	0.010	3.47	....	Colonial
30	S. A. E. 2320.....	0.20	0.65	0.18	0.018	0.014	3.37	....	Colonial
31	S. A. E. 3120.....	0.17	0.60	0.31	0.019	0.014	1.28	0.67	Colonial
32	Carbon Tool Steel.....	1.03	0.28	0.18	0.018	0.017	....	....	Colonial
33	Die Steel 'X'	0.64	0.64	0.132	0.016	0.017	....	1.07	Heppenstall
S1	Screw Stock Steel	0.30	0.70	0.225	0.063	0.083	....	....	Universal
S2	Screw Stock Steel	0.30	0.70	0.275	0.063	0.083	....	....	Universal
A1	Axle Steel	0.49	0.55	Trace	0.030	0.010	....	....	Universal
A2	Axle Steel	0.49	0.55	Trace	0.030	0.010	....	....	Universal
T1	Tool Steel	0.93	0.33	0.187	0.018	0.010	....	....	Universal
T2	Tool Steel	0.93	0.33	0.187	0.018	0.010	....	....	Universal
416	S. A. E. 1112, 1¼" Sq.....	.09-.13	.70-.90	....	.085-.120	.08-.40	....	....	
11-1	Cast Iron, 1 in. Sq.	Comb. .53	0.52	2.26	0.056	0.32	....	....	Univ. of Mich.

testing machines. The face of the steel disk is graduated at the periphery, so that the reading of the energy absorbed by taking a chip of any given material is read directly. The weight on the pendulum shaft was held in position by a set screw. For the position shown, the actual energy in foot-pounds absorbed by the chip is obtained by multiplying the scale reading by two. For the harder materials, the weight was moved to a position near the lower end of the pendulum shaft, for which position the scale reading was multiplied by three to obtain the correct value in foot-pounds. At least ten readings for each test specimen were averaged for the final value.

The Materials Tested

The materials tested consisted of a variety of carbon and alloy steels as one group and a variety of nonferrous metals as a second group. The steels are listed in Table 1, which also shows the chemical analysis of the steels. All of the steels down to, but not including S1, were from hot rolled bars 6 inches by 4 inches in section. All of these were in an annealed condition. The steels from S1 to T1, inclusive, were forged to a size of 1 inch by 2 inches in section and 14 inches long, after which they were annealed by cooling in lime and subsequently machined all over. They were then given an additional treatment as follows:

Bars S1 and S2 were normalized by heating to 1650 degrees Fahr. for one hour and cooled freely in air, annealed by heating to 1550 degrees Fahr. for ¾ of an hour and then cooled in the furnace.

Bars A1 and A2 were normalized by heating to 1550 degrees Fahr. for one hour and cooled freely in air, annealed by heating to 1450 degrees Fahr. for ¾ of an hour and then cooled in the furnace.

Bars T1 and T2 were normalized by heating to 1500 degrees Fahr. for one hour and cooled freely in air, annealed by heating to 1425 degrees Fahr. for ¾ of an hour and then cooled in the furnace.

Inasmuch as steels S1 and S2 have a sulphur content less than 0.075 to 0.150 per cent as called for by the A. S. T. M. specifications for Bessemer screw stock, bar No. 416, which is a Bessemer screw stock 1¼ inches square corresponding to S. A. E. specification 1112, was added. This bar was cold drawn with 1/16-inch draft. In order to show more clearly the relative values of the various physical properties of this group, a test piece of cast iron one inch square numbered 11-1 was also included. This test piece was made

Table II
Nonferrous Machinability Test Bars
Showing Chemical Anaylsis

Bar Mark	Material	Size	Chemical Analysis, Per Cent									
			Cu.	Zn.	Pb.	Tin	Fe.	Alum.	Ni.	Mn.	Mg.	Miscellaneous
50-A	Unleaded Drawing Brass	1¼" Hex.	65.5	34.15	0.25	.....	0.10	.....	.....	.....	.....	
187	Free-Cut. Screw Stock Brass ...	1½" Hex.	62.	35.	3.00	.....	.....	.....	.....	.....	.....	
187-A	187 Annealed Screw Stock Brass.	1½" Hex.	62.	35.	3.00	.....	.....	.....	.....	.....	.....	
X	Free-Cut. Screw Stock Brass ...	½" Sq.	62.	35.	3.00	.....	.....	.....	.....	.....	.....	
A3	Hi-Speed Screw Stock Brass....	15/16" Dia.	61.73	35.46	2.81	Trace	Trace	.....	.....	.....	.....	
S3	Hi-Speed Screw Stock Brass	15/16" Dia.	62.22	34.89	2.89	Trace	Trace	.....	.....	.....	.....	
26	½-Hard Sh. Brass, Rolled	½" thick	61.34	37.18	1.44	0.034	.....	.....	.....	.....	.....	
33	½-Hard Sh. Brass, Rolled	¾" thick	61.98	36.48	1.49	0.050	.....	.....	.....	.....	.....	
34	½-Hard Sh. Brass, Rolled	1" thick	64.10	34.34	1.52	0.042	.....	.....	.....	.....	.....	
2YB	Yellow Brass, Cast	2" dia.	70.	27.	2.	1.	.....	.....	.....	.....	.....	
2RB	Red Brass, Cast	2" dia.	80.	9.5	7.5	3.	.....	.....	.....	.....	.....	
5-SA	Bearing Bronze, Cast	2" Sq.	70.	.....	25.	5.	.....	.....	.....	.....	.....	
BB	Bearing Bronze, Cast	2" dia.	80.	.....	10.	10.	.....	.....	.....	.....	.....	
MB	Mang. Bronze, Cast	2" dia.	50-60	30-45	....	0.75	.....	0.40	.....	.05	.....	
GM	Gun Metal, Cast	2" dia.	90.	.....	....	10.	.....	.....	.....	.....	.....	6 oz. of 15% Ph-Cu. Alloy
Cu	Pure Annealed Copper	1½" Hex.	100.	.....	....	.....	.....	.....	.....	.....	.....	
N	Nickel, Rolled 'A'	2" dia.	.20	.....	....	.....	.45	.....	& Co. .99.	Trace	.....	S .008 Si. .10 C.10
M	Monel Metal, Rolled	2" dia.	28-29	.....	....	.....	.....	1.5 - 2.5	67-68	1.	.....	S .008 C = .05 / .20 Si. .03
A1-31	No. 31 Aluminum Alloy, Cast ..	2" dia.	3.	15.	....	.....	.....	82.	.....	.....	.....	
A1-12	No. 12 Aluminum Alloy, Cast ..	1" Sq.	8.	.....	....	.....	.....	91.	.....	.....	.....	
DM	Dow Metal "E", Cast	1.5" Dia.	.....	.....	....	.....	.....	6.0	.....	0.25	93.75	Impurities 1

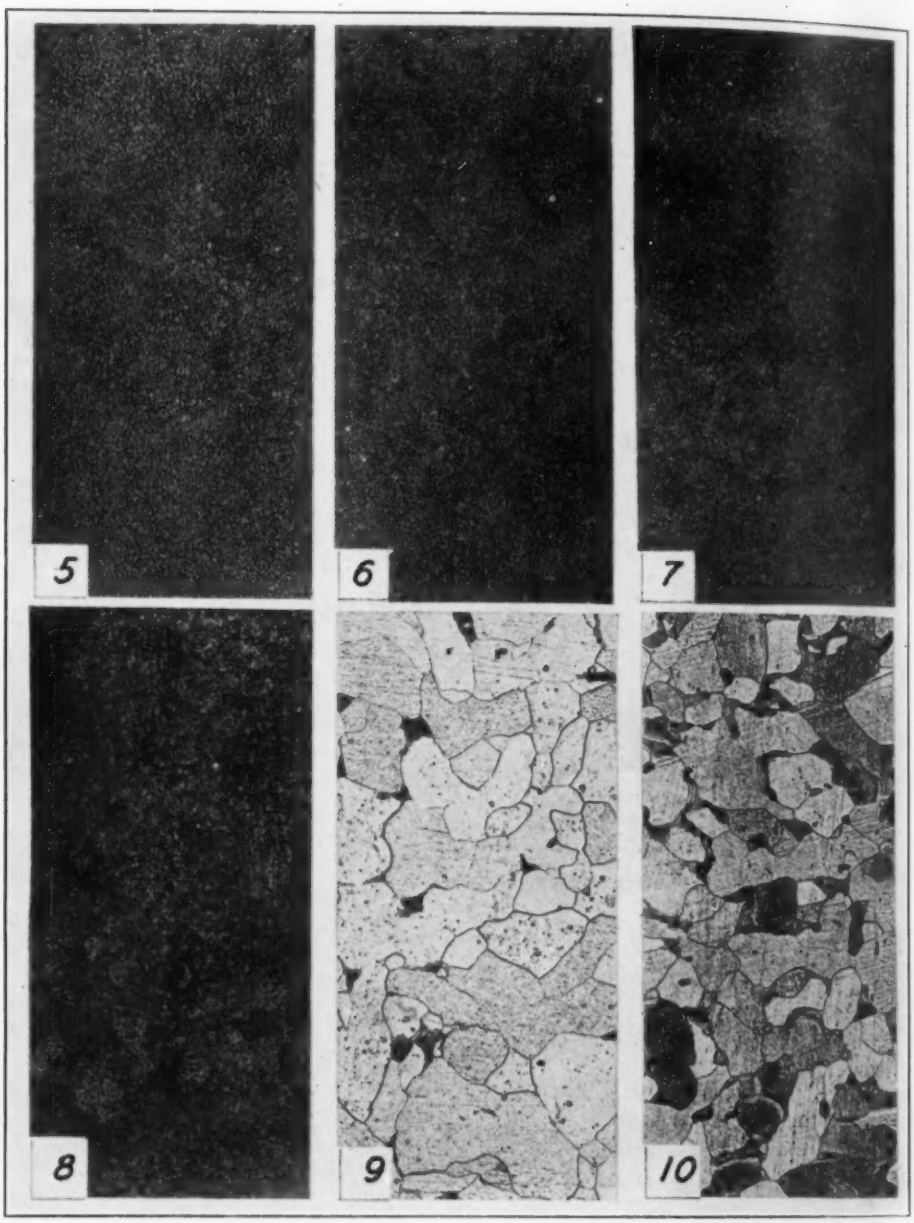
Table 111

Physical Properties of Steels

Bar Mark	Material	Tension Yield Point	Tension Ultim. Str.	Tension Red. of Area	Tension % Elong. in 2"	Compression Yield Point	Compression Ultim. Str.	Shear Ultim. Str.	Hardness (1) Brinell	Hardness (2) Rockwell	Hardness Scleroscope
2	'Standard' Tool Steel	36,500	77,350	50	30	30,000	111,000	64,000	152	85	25
11	0.15% Carbon, OH	24,500	52,000	66	41	.....	.....	39,400	102	56	22
111	0.15% Carbon, OH	23,000	51,300	67	40	.....	.....	39,400	101	58	21
11111	0.15% Carbon, OH	22,400	50,300	63	42	19,075	85,350	39,410	101	56	26
28	S. A. E. 1020	19,900	54,000	60	35	16,000	93,000	37,700	99	48	19
29	S. A. E. 2345	60,000	99,670	42.7	25	51,550	140,500	61,650	191	59	26
30	S. A. E. 2320	55,250	79,500	55.6	30	42,750	119,000	54,400	162	55	24
31	S. A. E. 3120	47,500	77,000	70.2	30.3	41,700	116,750	54,150	155	48	24
32	Carbon Tool Steel	39,170	80,000	56.7	32	42,000	112,000	52,670	155	52	25
33	Die Steel 'X'	37,500	105,000	1.4	15	39,200	130,000	49,000	190	94	30
S1	Screw Stock Steel	.....	.....	....	..	.....	.....	.....	146	77.9	20.2
S2	Screw Stock Steel	.....	.....	....	..	.....	.....	.....	148	77.4	19.8
A1	Axle Steel	.....	.....	....	..	.....	.....	.....	145	74.3	21.2
A2	Axle Steel	.....	.....	....	..	.....	.....	.....	141	74	21.4
T1	Tool Steel	.....	.....	....	..	.....	.....	.....	188	87.6	24.2
T2	Tool Steel	.....	.....	....	..	.....	.....	.....	189	87.1	26.0
416	S. A. E. 1112, 1¼" Sq.	.....	.....	....	..	.....	.....	.....	196	94.5	30.0
11-1	Cast Iron, 1 in. sq.	.....	.....	....	..	.....	.....	.....	207	97.5	39.

(1) 10 mm. ball, 3000 kg.

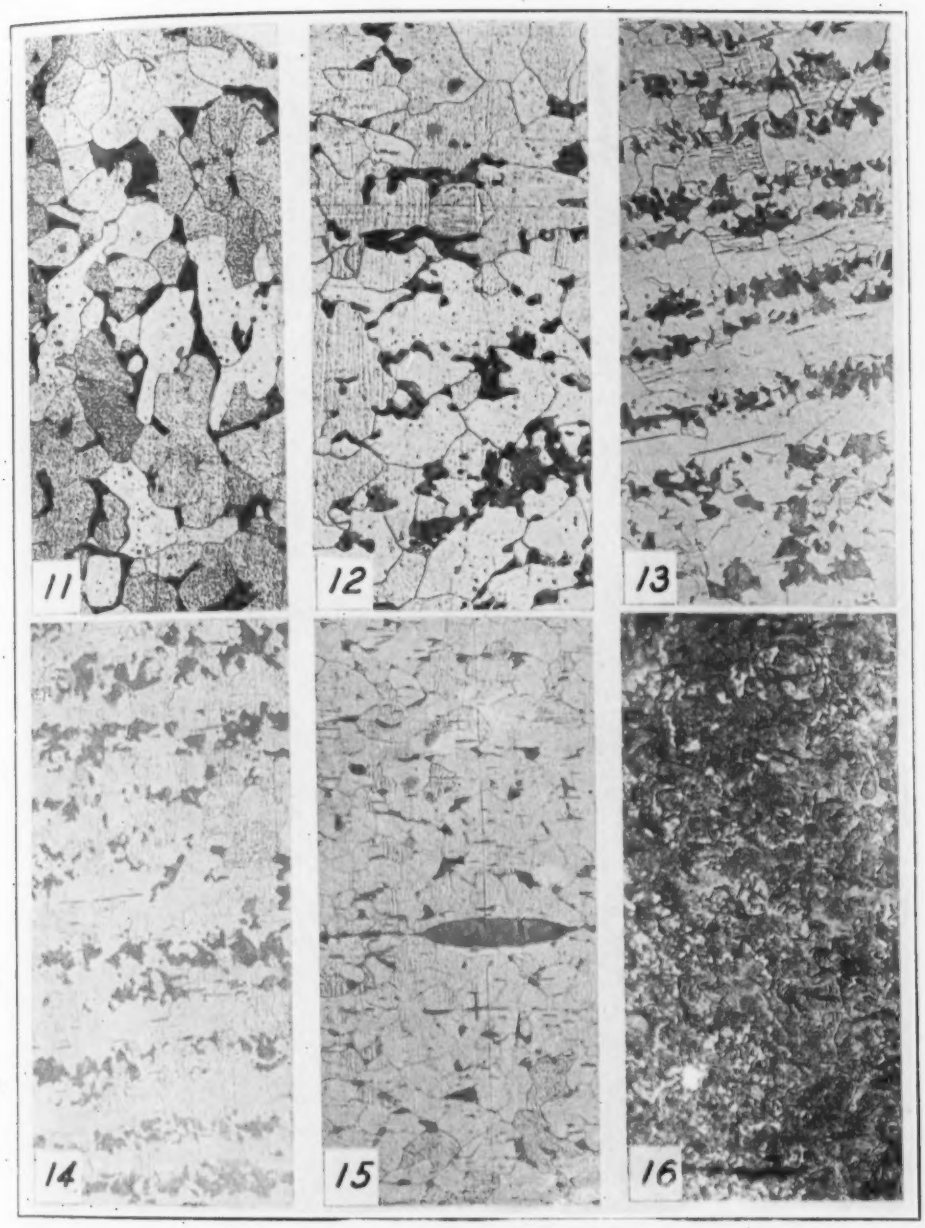
(2) B scale, 1/16 in. ball, 100 kg.



Photomicrographs of the Steels × 100.

Fig. 5—Bar 2, Tool Steel. Shows Sorbitic (or Granular Pearlite), Fine-Grained and Uniform.
Fig. 6—Bar 32, Tool Steel. Sorbitic (or Granular Pearlite), Very Uniform.
Fig. 7—Bar T2, Tool Steel. Sorbitic, Fine-Grained and Uniform
Fig. 8—Bar T1, Tool Steel. Pearlitic, Coarse-Grained.
Fig. 9—Bar 11, 0.15 Per Cent Carbon Steel. Pearlite and Ferrite.
Fig. 10—Bar 11111. Same as Fig. 9.

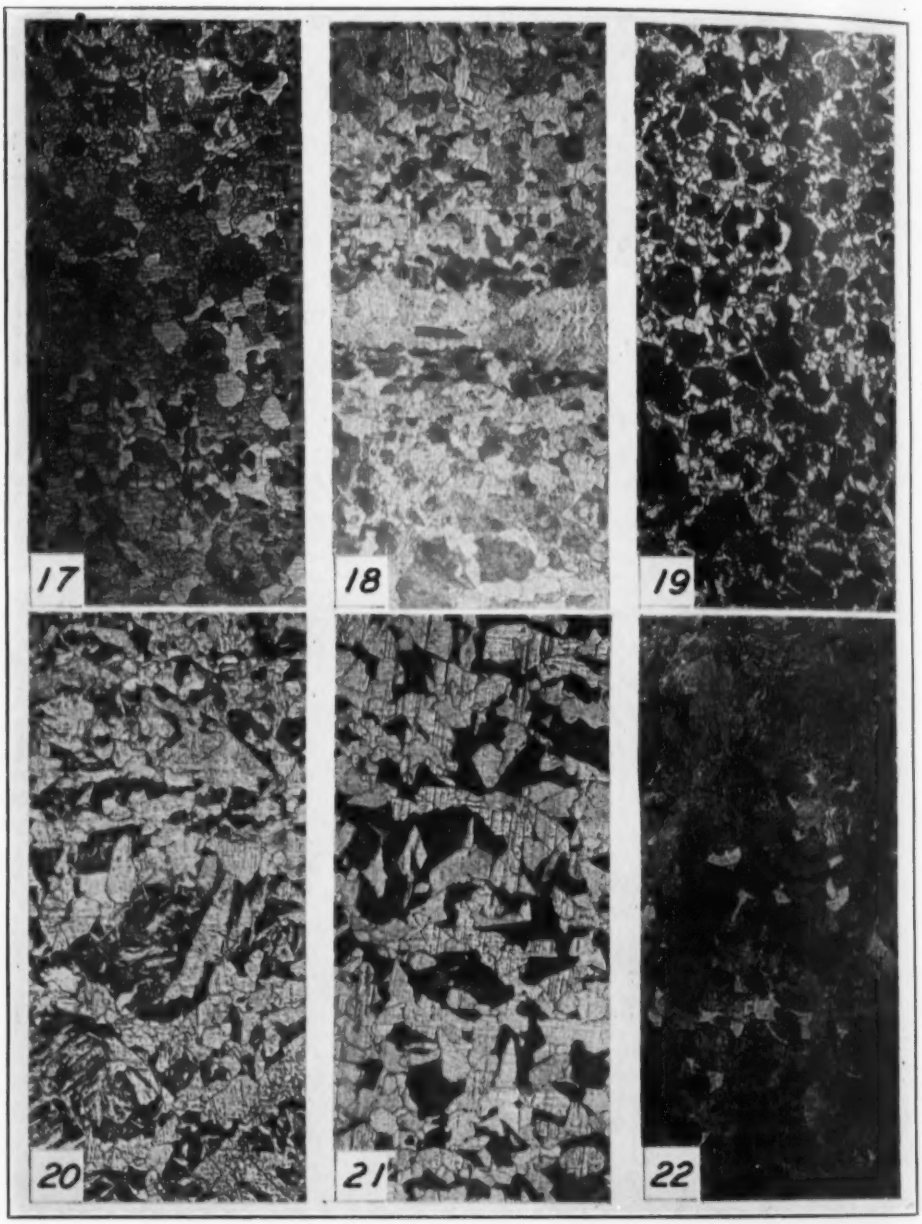
of a mixture to give a soft iron for machining purposes. The physical properties of this group of steels are tabulated in Table III.



Photomicrographs of the Steels × 100.

Fig. 11—Bar 111. Same as Fig. 9.
Fig. 12—Bar 28, S.A.E. 1020. Ferrite and Pearlite. Pearlite Unevenly Distributed.
Fig. 13—Bar S1, Screw Stock Steel. Pearlite and Ferrite in Banded Structure with Slag Streaks in the Ferrite Bands.
Fig. 14—Bar S2, Screw Stock S Steel. Same as Fig. 13.
Fig. 15—Bar 416, S.A.E. 1112. Pearlite and Ferrite. Small and Large Slag Streaks.
Fig. 16—Bar 11-1. Cast Iron Pearlite, Ferrite and Graphite.

Photomicrographs of the seventeen steels and one cast iron are given in Figs. 5 to 22, inclusive. All pictures are taken at a magni-



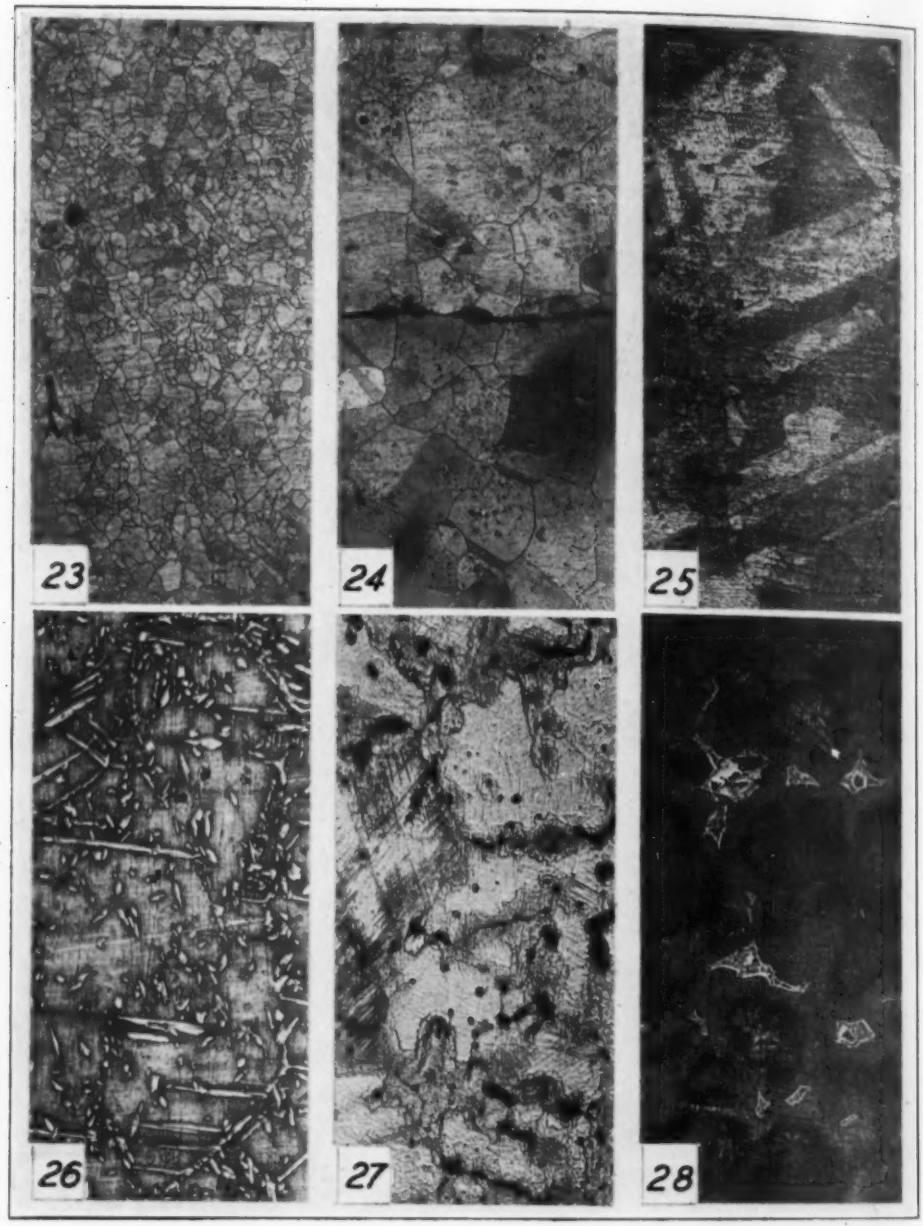
Photomicrographs of the Steels × 100.

Fig. 17—Bar A1, Axle Steel. Grain Size Non-uniform.
Fig. 18—Bar A2, Axle Steel. Ferrite Band Carrying Slag.
Fig. 19—Bar 29, S.A.E. 2345. Pearlitic.
Fig. 20—Bar 30, S.A.E. 2320. Pearlitic. Not Well Annealed.
Fig. 21—Bar 31, S.A.E. 3120. Pearlitic.
Fig. 22—Bar 33, Die Steel. Small Amount of Ferrite, Unevenly Distributed.

fication of 100 diameters and the samples were etched for fifteen seconds in 4 per cent nitric acid in alcohol. All photomicrographs

Table IV
Physical Properties of Nonferrous Metals

Bar Mark	Material	Tension				Compression		Shear	Hardness		
		Yield Point	Ultim. Str.	Red. of Area	% Elong. in 2"	Yield Point	Ultim. Str.	Ultim. Str.	Brinell 500Kg. 10mm	Rockwell 'B' Scale	Scler-oscope
50-A	Unleaded Drawing Brass	.....	.....	....	....	.....	.....	.....	50.9	61	12.7
187	Free-Cut. Screw Stock Brass	.....	.....	....	....	.....	.....	.....	60.4	95.5	25.0
187-A	187 Annealed Screw Stock Brass	.....	.....	....	....	.....	.....	.....	49.9	63.	12.6
X	Free-Cut. Screw Stock, Brass	.....	.....	....	....	.....	.....	37,100	105	100.5	40.4 to 36
A3	Hi-Sp. Brass Screw Stock	.....	56,900	....	24	.....	.....	.....	93	95.	24.
S3	Hi-Sp. Brass Screw Stock	.....	64,050	....	20	.....	.....	.....	109	100.	26.
26	½-Hard Sh. Brass, Rolled	35,000	58,000	32	31	.....	.....	35,600	109	102.	24
33	½-Hard Sh. Brass, Rolled	25,500	44,877	36	....	.....	.....	28,360	65	84.	17
34	½-Hard Sh. Brass, Rolled	57,300	59,831	29	....	.....	.....	36,060	114	99.	24
2YB	Yellow Brass, Cast	.....	.....	....	....	.....	.....	.....	45	55.	14
2RB	Red Brass, Cast	18,080	29,000	23	14	.....	.....	.....	61	51.	13
5-SA	Bearing Bronze, Cast	14,800	22,600	9.5	10	.....	.....	.....	33.6	13.	8
BB	Bearing Bronze, Cast	22,600	34,600	14.8	12.3	.....	.....	.....	67	62.	19
MB	Mang. Bronze, Cast	.....	.....	....	....	.....	.....	.....	130	95.	25
GM	Gun Metal, Cast	.....	.....	....	....	.....	.....	.....	74	83.	23
Cu	Pure Annealed Copper	.....	.....	....	....	.....	.....	.....	40.4	28.	6
N	Nickel, Rolled 'A'	25,000	70,000	50	30	.....	.....	.....	143	105.	24
M	Monel Metal, Rolled	50,000	90,000	55	42	.....	.....	.....	130	106.	29
A1-31	No. 31 Aluminum Alloy, Cast	.....	.....	....	....	.....	.....	.....	73	88.	22
A1-12	No. 12 Aluminum Alloy Cast	18,455	19,046	6	1.6	.....	.....	.....	63	77.	14
DM	Dow Metal "E", Cast	11,000	28,000	....	7	.....	42,000	.....	48	54.	20



Photomicrographs of Nonferrous Metals. × 100.

Fig. 23—Bar M, Monel Metal. Corroded.
Fig. 24—Bar N, Rolled "A" Nickel. Badly Pitted and Seamed.
Fig. 25—Bar Cu, Pure Annealed Copper. Poorly Polished and Etched.
Fig. 26—Bar MB, Manganese Bronze.
Fig. 27—Bar 2RB, Cast Red Brass. Polishing Bands in Coarse Dendritic Structure.
Fig. 28—Bar GM, Cast Gun Metal. Alpha plus Alpha and Delta Eutectoid back ground.

are taken on a surface approximately one half inch from the outside surface running parallel to the length of the bar. They are arranged

in groups of like materials to make direct comparison easy. Figs. 5 to 8, inclusive, are the carbon tool steels. Figs. 9 to 14, inclusive, are the low carbon steels. Fig. 15 is the screw stock. Fig. 16 is the cast iron. Figs. 17 and 18 are the medium carbon steel. Figs. 19 to 22 are the alloy steels.

The nonferrous metals are listed in Table II. The chemical analysis of each bar is shown. The size of each bar is also given in this table, as in some instances it may have an important influence upon the results of the machinability tests. Bars 187 and X are, for instance, the same brass, but X has been cold drawn to a greater extent. It is expected that this additional cold working throughout the entire cross section of the piece will give a more uniform grain size. It is also expected that the brass of high lead content should show superior machining qualities. Bars A3 and S3 are of the same general type of high speed or free-cutting screw stock brass, but made by different companies. The physical properties of these nonferrous metals are given in Table IV.

Photomicrographs of the nonferrous metals are shown in Figs. 23 to 43, inclusive. Again, each picture was taken on a surface parallel to the longitudinal axis of the bar and approximately one half inch below the outside surface. All brass bars were etched with ammonia plus hydrogen peroxide. The bronzes, 5Sa, BB, and MB, were etched with acid ferric chloride. The gun metal, GM, was etched with ammonia plus hydrogen peroxide, followed with acid ferric chloride. The pure annealed copper was etched with ammonia plus hydrogen peroxide. The nickel, N, and monel metal, M, were given a 2-minute etch in acid ferric chloride. The aluminum specimens, Al-31 and Al-12, and the Dow metal, DM, were unetched. All structures are shown at 100 diameters of magnification. The photomicrographs of the nonferrous metals are arranged in groups of like metals, where possible, to permit comparisons.

Machinability Data

The results of the various machinability tests are shown for the steel group in Table V and for the nonferrous group in Table VI. These data were determined by measuring the force on a planer tool, the torque and thrust of a ¾-inch diameter drill, the penetration in inches per 100 revolutions per minute, of a ¼-inch diameter drill and the energy in foot-pounds required to remove a chip by milling.

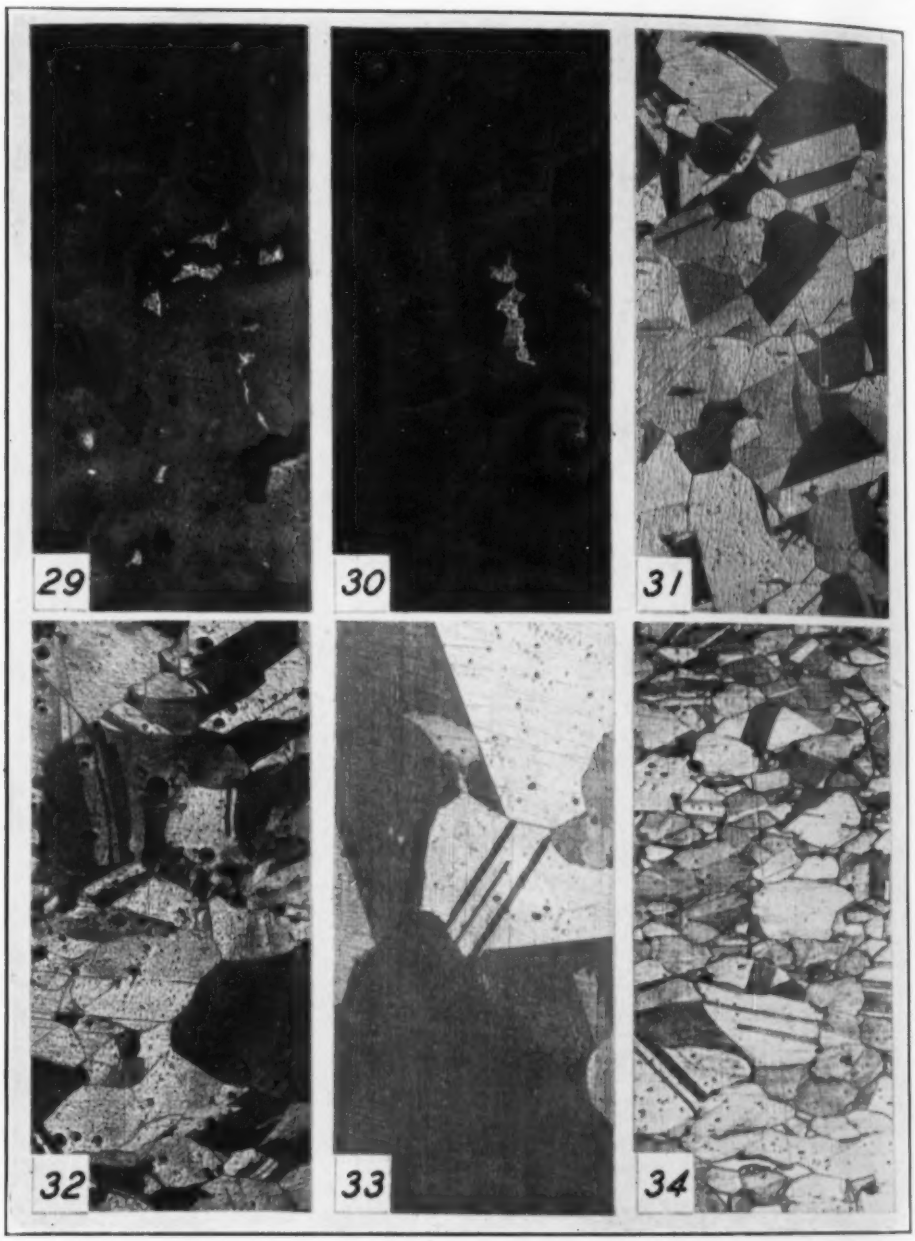
The total force "F" on a planer tool is the value in pounds actu-

Table V
Machinability Data for Steels

Bar Mark	Material	Force on Planer Tool: Total Lbs. 'F'	Force on Planer Tool: Unit Lbs. 1/1000 Sq. In. 'U'	Force on Planer Tool: H. P. per cu. in. per minute	Drilling: Torque Ft. lbs. 'T'	Drilling: Thrust Lbs. 'Th'	Drilling: Net H. P. per cu. inch per min.	Drill Penetration in. per 100 rpm	Milling: Ft. Lbs. per chip 'E'	Milling: H. P. per cu. in. per min.
2	Tool Steel	2,445	489.0	1.235	40.	1400	1.442	0.0615	58.02	5.628
11	0.15% Steel	2,240	448.0	1.131	24.	1500	1.228	0.07843	44.574	4.324
111	0.15% Steel	1,937	387.4	0.978	32.	1000	1.152	0.07830	41.850	4.060
11111	0.15% Steel	2,090	418.0	1.055	33.	1100	1.19	0.08053	42.450	4.115
28	S. A. E. 1020	1,724	344.8	0.870	32.5	1000	1.170	0.08333	34.965	3.393
29	S. A. E. 2345	1,830	366.0	0.923	30.5	1250	1.10	0.07570	32.910	3.193
30	S. A. E. 2320	1,749	349.8	0.884	28.5	1100	1.03	0.06890	45.090	4.374
31	S. A. E. 3120	1,702	340.4	0.859	30.	1100	1.081	0.07673	31.956	3.100
32	Tool Steel	2,394	478.8	1.209	39.	1500	1.409	0.0545	50.130	4.860
33	Die Steel	1,720	344.0	0.868	29.	1300	1.046	0.07040	34.005	3.315
S1	Screw Stock Steel	1,760	352.0	0.889	27.5	1000	.981	0.09155	32.025	3.120
S2	Screw Stock Steel	1,737	347.4	0.876	27.	1000	.974	0.09205	31.50	3.053
A1	Axle Steel	1,745	349.0	0.881	29.5	1000	1.063	0.07575	36.440	3.532
A2	Axle Steel	1,754	350.8	0.886	28.5	1000	1.029	0.07942	37.992	3.685
T1	Tool Steel	2,244	448.8	1.132	37.	1200	1.333	0.05075	46.050	4.470
T2	Tool Steel	2,263	452.6	1.142	38.	1200	1.371	0.05726	45.10	4.375
416	S. A. E. 1112	1,475	295.0	0.745	24.5	1000	.884	0.13477	36.774	3.566
11-1	'Cast Iron'	1,022	204.4	0.516	17.	600	.614	0.1863	18.225	1.770

Table VI
Machinability Data for the Nonferrous Metals

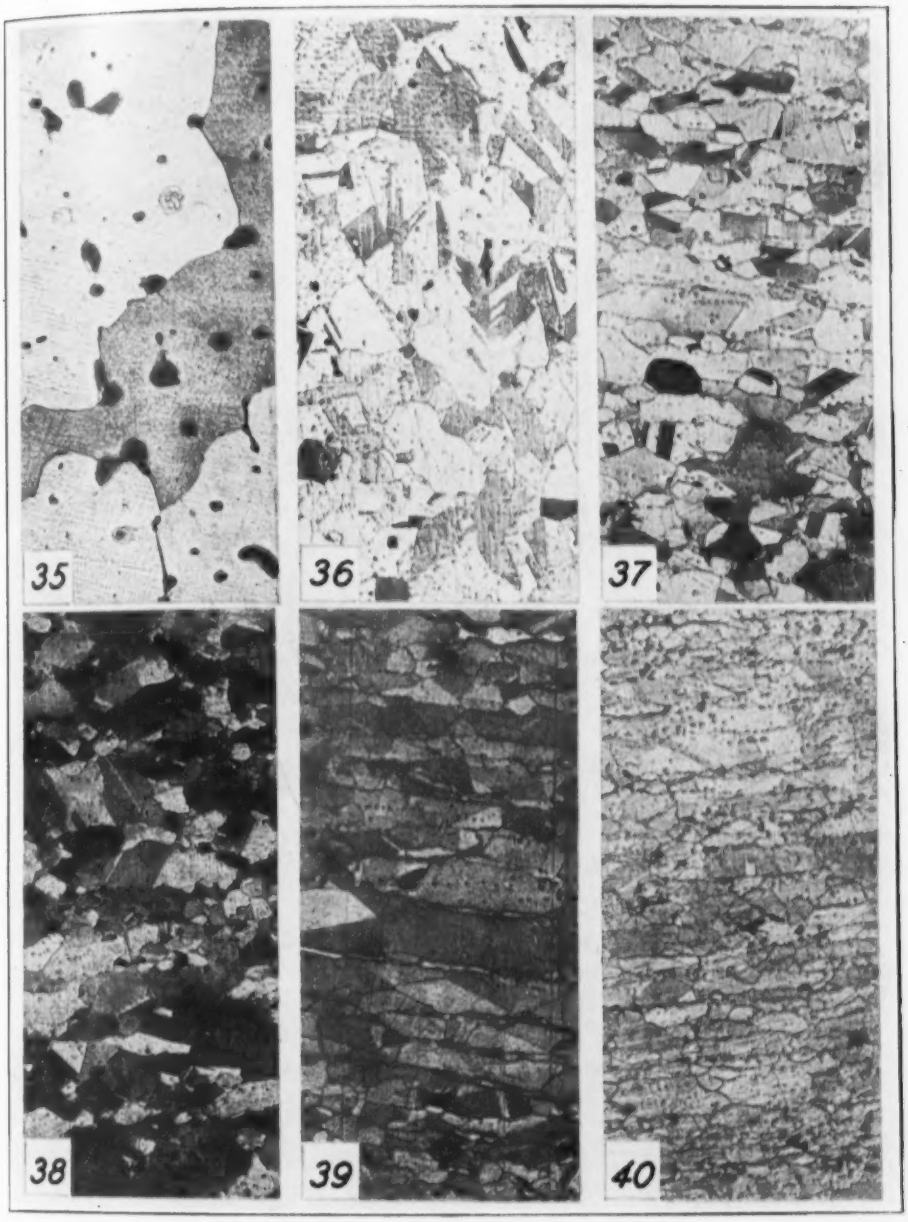
Bar Mark	Material	Force on Planer Tool: Total Lbs. 'F'	Force on Planer Tool: Unit Lbs. 1/1000 Sq. In. 'U'	Force on Planer Tool: H. P. per cu. in. per minute	Drilling: Torque Ft. lbs. 'T'	Drilling: Thrust Lbs. 'Th'	Drilling: Net H. P. per cu. inch per min.	Drill Penetration in. per 100 rpm	Milling: Ft. Lbs. per chip 'E'	Milling: H. P. per cu. in. per min.
50-A	Unleaded Brass	1,163	232.6	0.5875	30.	1100	1.081	0.0475	23.81	2.3060
187	Brass Screw Stock	567	113.4	0.2863	8.75	325	.316	0.42336	12.60	1.2220
187-A	Brass Screw Stock Annealed	581	116.2	0.2937	9.	300	.324	0.47566	11.93	1.159
X	Brass Screw Stock	563	112.6	0.2840	8.5	300	.305	0.4347	13.10	1.270
A3	Brass Screw Stock	574	114.8	0.2899	6.5	300	.234	0.3546	10.245	0.9935
S3	Brass Screw Stock	575	115.0	0.2902	8.	300	.288	0.3497	11.310	1.0965
26	Sheet Brass	587	117.4	0.2962	10.5	450	.379	0.2620	11.400	1.1060
33	Sheet Brass	595	119.0	0.3002	13.	600	.47	0.3319	11.289	1.0940
34	Sheet Brass	609	121.8	0.3070	11.	600	.398	0.2453	12.570	1.2190
2YB	Yellow Brass	557	111.4	0.2816	10.	400	.361	0.2446	15.450	1.4995
2RB	Red Bronze	617	123.4	0.3117	10.75	500	.389	0.3700	10.950	1.0620
5SA	Bearing Bronze	379	75.8	0.1915	6.	200	.217	0.65325	8.160	0.7920
BB	Bearing Bronze	503	100.6	0.2541	8.	250	.288	0.3283	13.380	1.2975
MB	Manganese Bronze	750	150.0	0.3789	23.	1200	.832	0.0307	16.305	1.5830
GM	Gun Metal	564	112.8	0.2847	19.	800	.685	0.0047	18.480	1.7930
Cu	Annealed Copper	1,875	375.0	0.9467	50.	1400	1.80	0.1249	32.88	3.1875
N	Nickel "A"	3,140	628.0	1.586	65.	2100	2.34	0.0394	54.360	5.2740
M	Monel Metal	3,335	667.0	1.684	41.	1400	1.475	0.0288	52.17	5.0680
A1-31	Aluminum Alloy	648	129.6	0.3270	11.	600	.398	0.344	9.345	0.9065
A1-12	Aluminum Alloy	552	110.4	0.2790	8.5	375	.305	0.4586	9.390	0.9118
DM	Dow Metal	250	50.0	0.1264	5.	250	.180	0.4933	6.00	0.5817



Photomicrographs of Nonferrous Metals. × 100.

Fig. 29—Bar BB, Cast Bearing Bronze. Alpha and Delta Eutectoid Constituents Evenly Distributed.
Fig. 30—Bar 5-Sa, Cast Bearing Bronze. Very Small Amount of Alpha and Delta Eutectoid.
Fig. 31—Bar 50A. Unleaded Drawing Brass. Alpha.
Fig. 32—Bar 34, Rolled Sheet Brass. Alpha.
Fig. 33—Bar 33, Rolled Sheet Brass. Very Coarse-Grained.
Fig. 34—Bar 26, Rolled Sheet Brass. Alpha plus Beta.

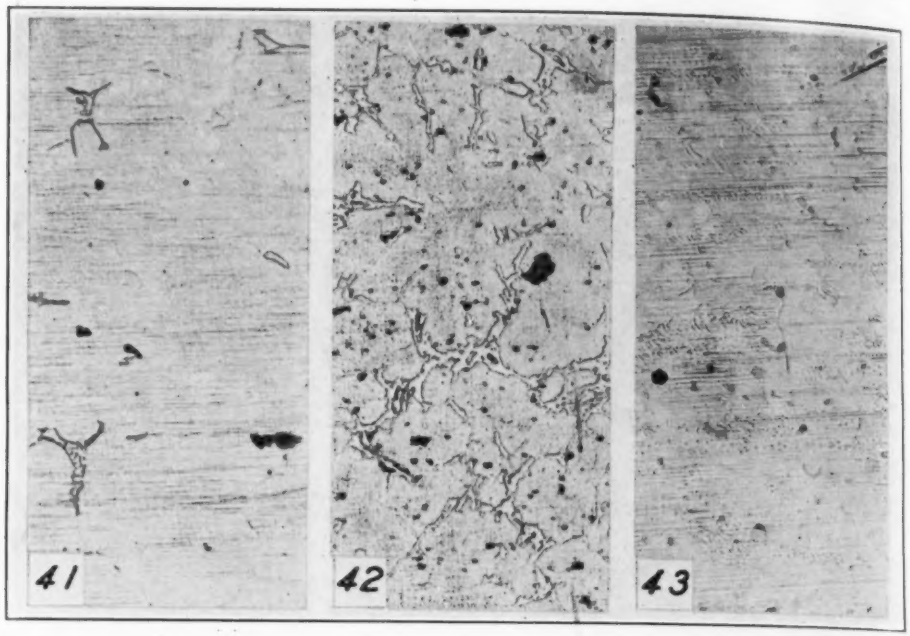
ally exerted in the direction of cut on the planer tool ½ inch wide



Photomicrographs of Nonferrous Metals. × 100.

Fig. 35—Bar 2 YB, Cast Yellow Brass. Coarse, Dendritic.
Fig. 36—Bar 187-A. 187 Annealed.
Fig. 37—Bar 187, Free Cutting Brass Screw Stock. Alpha plus Beta.
Fig. 38—Bar X, Free Cutting Brass Screw Stock. Alpha plus Beta.
Fig. 39—Bar A3, High-speed Brass Screw Stock, Alpha plus Beta.
Fig. 40—Bar S3, Similar to Fig. 39.

when taking a depth of cut of 0.010 inches at a cutting speed of 20 feet per minute. The unit force "U" is the number of pounds exerted on 0.001 square inch of cross sectional area of the chip.



Photomicrographs of Nonferrous Metals. × 100.
Fig. 41—Bar A1-31, No. 31 Aluminum Alloy, Cast, Unetched.
Fig. 42—Bar A1-12, No. 12 Aluminum Alloy, Cast, Unetched.
Fig. 43—Bar DM, Dow Metal "E," Cast, Unetched.

$$U = \frac{F}{1000\,WD} = \frac{F}{5}$$

in which W = width of cut 0.5 inches, and "D" the depth of cut, 0.010 inches.

For tool steel, Bar 2,

$$U = \frac{2445}{5} = 489 \text{ pounds}$$

This unit force of 489 pounds per 1/1000 square inch of chip area is equivalent to 489,000 pounds per square inch of chip area. The horsepower developed by the planer tool equals

$$\frac{FS}{33{,}000}$$

in which "F" is the total force on the tool in the direction of the cut in pounds and "S" is the cutting speed in feet per minute. As "S" equals 20,

$$\text{H. P.} = \frac{F}{1650}$$

For tool steel, Bar 2, the

$$\text{H. P.} = \frac{2445}{1650} = 1.482$$

The cubic inches of metal removed per minute $=WDL = 0.5 \times 0.010 \times 20 \times 12 = 1.2$, in which "L" is the length of cut per minute in inches and equals 12S. The horsepower per cubic inch of metal removed per minute equals the total power developed divided by the cubic inches of metal removed per minute, or

$$\frac{F}{1.2 \times 1650} = \frac{F}{1980}$$

For tool steel, Bar 2, the H. P. per cubic inch of metal removed per minute is then

$$\frac{2445}{1980} \text{ or } 1.235$$

To reduce the experimental data for the drill torque and thrust to net horsepower per cubic inch of metal removed per minute, the following method was used. The total horsepower developed at the point of drill is the sum of that due to torque and thrust. The horsepower of the torque

$$\text{H. P.}_t = \frac{2\pi TN}{33{,}000} = \frac{2\pi \times 152T}{33{,}000} = 0.02894\ T,$$

in which T equals the torque in foot-pounds and N equals the actual revolutions per minute of the drill. The horsepower of the thrust equals the thrust times the distance travelled per minute divided by 33,000 or

$$\text{H. P.}_{th} = \frac{fN \text{ Thrust}}{33{,}000} = \frac{0.012 \times 152\ Th}{33{,}000 \times 12} = 0.000004606\ Th.$$

in which Th equals the thrust in pounds, f equals the feed in inches per revolution of the drill, and N equals the revolutions per minute of the drill. The total net horsepower H. P. $= 0.02893T + 0.000004606Th$.

The cubic inches of metal removed per minute equals

$$\frac{\pi d^2}{4}. \text{ f.N.} = \frac{\pi (3/4)^2}{4} \times 0.012 \times 152 = 0.8068$$

in which d is the diameter in inches of the hole drilled, F is 0.012 the feed in inches per revolutions per minute and N is 152 the revolutions per minute of the drill.

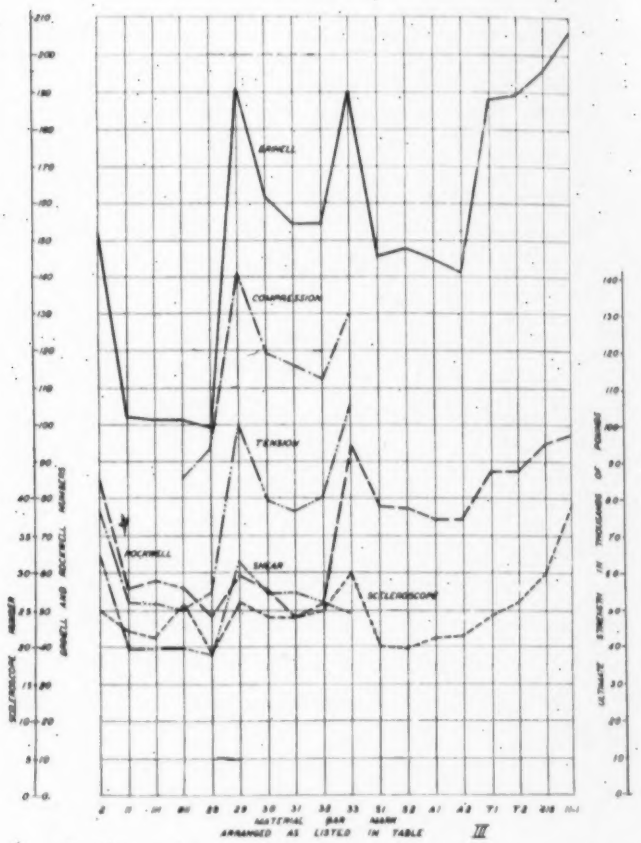


Fig. 44—Curves Showing Physical Properties of Steels, Hardness and Ultimate Strength.

The net horsepower per cubic inch of metal removed per minute in drilling with a ¾-inch drill rotating at 152 revolutions per minute, and having a feed of 0.012 inches per revolution, for tool steel, Bar 2, of Table V, for which there is a torque of 40 foot-pounds and a thrust of 1400 pounds, is

$$\frac{0.02894T + 0.000004606\,Th}{0.8068} = \frac{1.1576 + 0.00645}{0.8068} = \frac{1.164}{0.8068} = 1.442$$

For determining the horsepower per cubic inch of metal removed per minute in milling, using the experimental data, it is necessary to make the following assumptions, which include the conditions under which the experiments were run.

d = the depth of cut = 0.125 inches
w = the width of cut = 0.250 inches
f = the feed per tooth = 0.010 inches

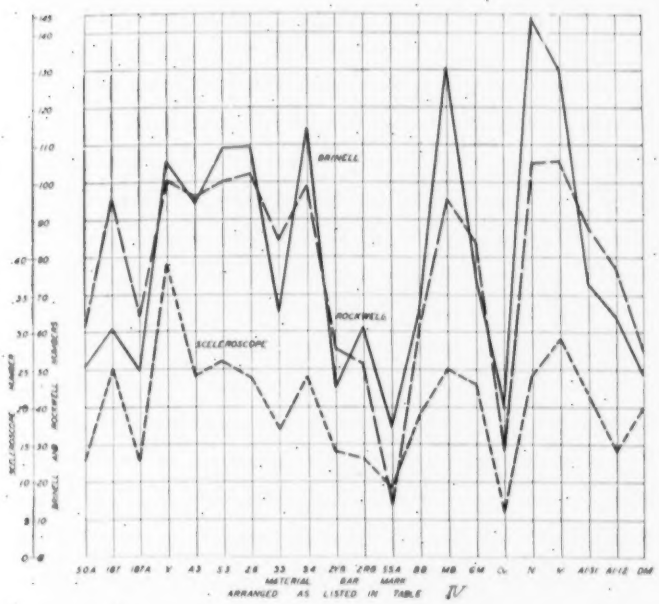


Fig. 45—Curves Showing Physical Properties of Nonferrous Metals, Hardness.

A cutter is assumed to have 14 teeth and to rotate at 58.3 revolutions per minute, giving 816.2 chips per minute. The horsepower developed equals

$$\frac{816.2}{33{,}000} \times E = 0.024733\ E,$$

in which E is the energy in foot-pounds required to remove one chip. For tool steel, Bar 2, the horsepower developed is $0.024733 \times 44.175 = 1.606$.

The cubic inches of metal removed per minute equals $dwftN = 0.125 \times 0.250 \times 0.010 \times 14 \times 58.3 = 0.255$, in which t is the number of teeth in the cutter, and N is the revolutions per minute of the cutter.

Therefore, the horsepower per cubic inch of metal removed per minute

$$= \frac{0.024733\ E}{0.255} = 0.097\ E.$$

For the tool steel, Bar 2, this becomes $0.097 \times 58.02 = 5.628$, as shown in Table V.

Discussion of Machinability Data

Fig. 44 illustrates graphically the physical properties of the steels. The materials were arranged as abscissa, as listed in Table III. Over each material as ordinate, are plotted the scleroscope, Brinell, and Rockwell numbers, as well as the ultimate strengths in tension, compression, and shear. It is observed that, with the possible exception of the scleroscope number, there is a similarity between the various ordinates, that is, when the Brinell number is high, the ultimate strength in tension, compression, and shear is high, as well as the Rockwell and scleroscope numbers. The scleroscope reading for bar 2, which is a one per cent carbon tool steel, is low when compared relatively with the other physical properties.

The Brinell, Rockwell, and scleroscope hardness numbers are plotted as ordinates over the nonferrous metals arranged as listed in Table IV in Fig. 45. Here again is seen a general similarity of values, although as before there are some wide variations. For instance, the scleroscope reading for Dow metal is higher than that for Al-12, whereas the Brinell and Rockwell numbers are both considerably lower. Again, it is seen that the Brinell for bar 33 is relatively low, but for bar 2-RB is relatively high. Because of the limited funds available, tensile and shear tests were not made on the nonferrous metals.

In order to give a general impression as to the relation existing between the various machining properties of the metals, these values are plotted as ordinates over the bar number as abscissa in Fig. 46. The bars are arranged as abscissas in order of decreasing force on the planer tool, that is, bar No. 2, at the extreme left has the highest planer tool force, while bar No. 11-1 at the extreme right has the lowest planer force. By trial and error, this arrangement seemed to be the best for showing the general relation between these different properties. The Brinell number is plotted over each bar at the top of the figure. It is to be noted that the Brinell number does not vary directly with the force on the planer tool, as the Brinell number of Bar 11-1 (cast iron) has the lowest planer tool force, but the highest Brinell number. Further, it is seen that those materials having the highest Brinell numbers of approximately the same value, that is, bars T2, T1, 29, and 33 are at some distance along the abscissa axis from one another, while bar 28 having the lowest Brinell number is some distance from bars No. 11, 11111, and 111, which have the

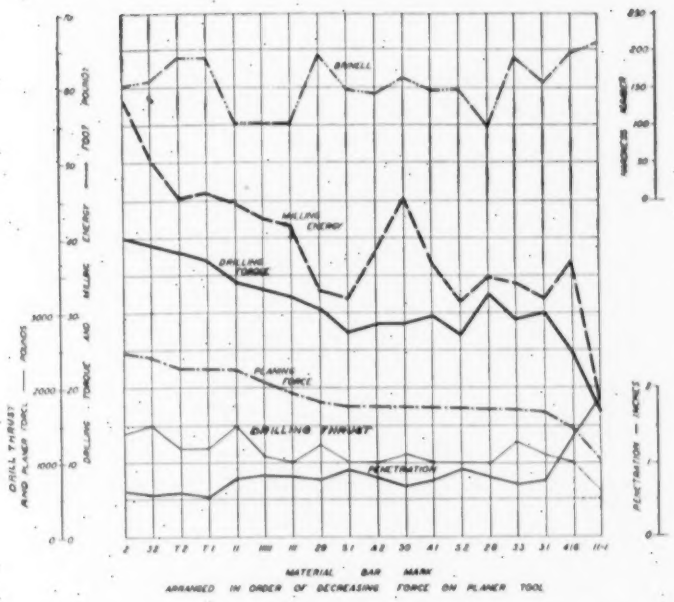


Fig. 46—Curves Showing Machining Properties of Steel.

next lowest Brinell numbers which are approximately the same value. The curve for milling, which represents the energy in foot-pounds required to remove a single chip, follows in a general way the planing force curve. Bars 29 (a 3½ per cent nickel and 0.45 per cent carbon steel) and S1 (a low carbon steel) appear to be out of order, as their values are among the lowest five on the curve.

The energy required to remove a chip of bar 30 (a 3½ per cent nickel and 0.20 per cent carbon steel) by milling is nearly as great as the two tool steels T2 and T1. The value was checked repeatedly, however. The penetration or the number of inches that the ¼-inch drill would penetrate the material under a 93.75-pound load for 100 revolutions is just the reverse of the other force and energy curves. It naturally would be assumed that the more a material resists the cutting force of a tool, the less would be the drill penetration, so that the penetration curve would be an inverse function of the force or energy curves. The drill penetration for bar No. 30 is low, in fact lower than all materials to the left up to T1. The milling value for 30 is higher than for any other bar to the left up to T1. The drill penetration for bar 2 (tool steel) is higher than that for bars 32, T2, and T1 (all tool steels), while the planing force for bar 2 is highest of all; the drill torque for bar 2 is highest of all; and the milling energy for bar 2 is highest of all. The penetra-

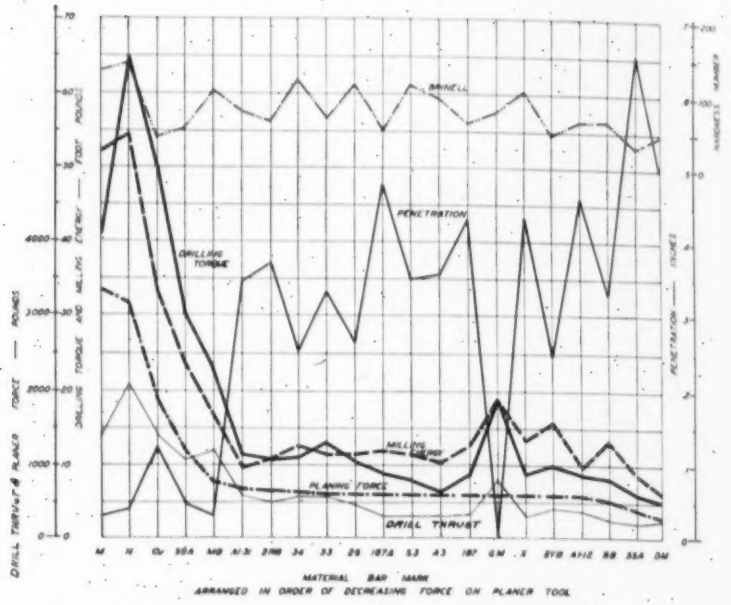


Fig. 47—Curves Showing Machining Properties of Nonferrous Metals.

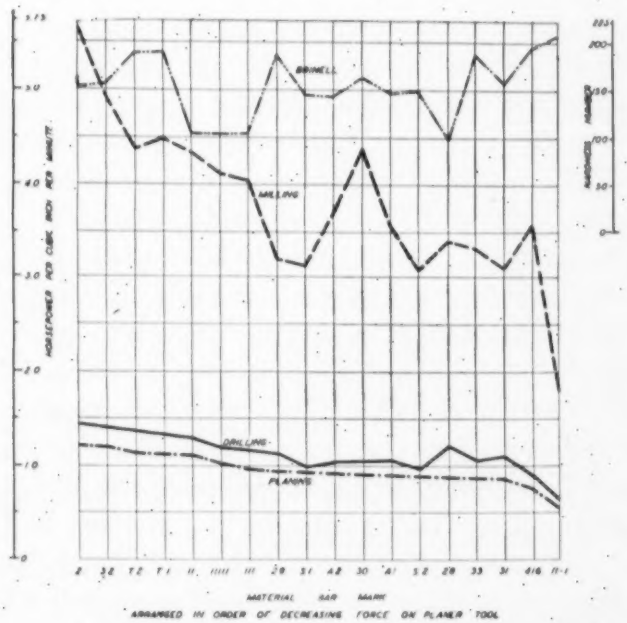


Fig. 48—Curves Showing Power Required to Cut Steel.

tion for bars 11, 11111, and 111 appears to be the same. The planing force for bar 11 is greater than that for 11111 and 111, and parallels the drilling torque and milling energy curves. It is also noted that the Brinell numbers for these three materials are the

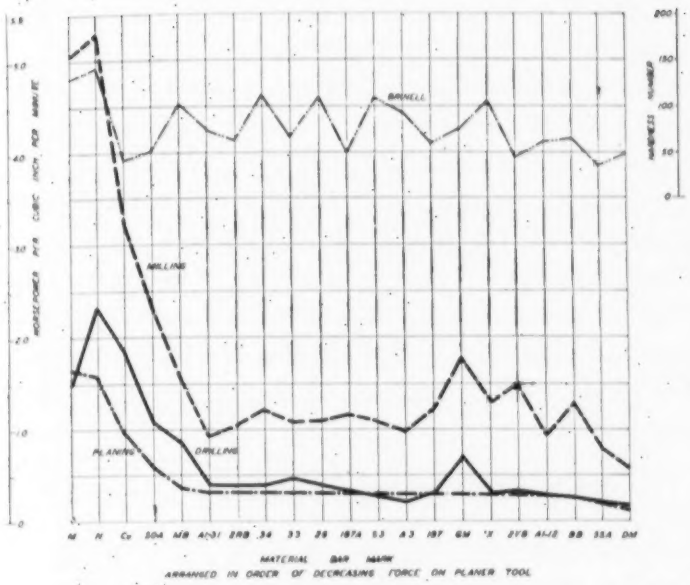


Fig. 49.—Curves Showing Power Required to Cut Nonferrous Metals.

same. The drop in Brinell number from T1 to 11 is marked. The drop in the milling and drilling curve is also marked, while the drop in the planing curve is negligible from T1 to 11. The drill penetration for 11 is much greater, however, than that for T1. The Brinell number may, in some instances, indicate the trend of the milling, drilling, planing, and penetration values, although such a relation is not constant or dependable. The four bars at the extreme right in Fig. 46 are good illustrations, because the Brinell curve is relatively high, being considerably above the average, while the milling, drilling, and planing curves are low and the drill penetration is high.

The machining properties of the nonferrous metals are shown in Fig. 47. The materials are arranged on the abscissa axis in order of decreasing force on the planer tool, while the ordinates are arranged to accommodate the planer force, drilling torque, milling energy, drill penetration, and Brinell hardness number, which are tabulated in Table VI. Bar M (monel) has the highest planing force. The other machining properties, however, are less for monel than for N (nickel). Bar GM (gun metal) has a Brinell number of average value compared to the other metals and also has a planing force comparable with the majority of the nonferrous metals. The drill penetration, however, drops practically to zero and the milling energy and drilling torque are considerably above the average of the

values for the materials in this region. It is also seen that the Brinell hardness of copper is second lowest, only 40.4, and the drill penetration is 0.1249 inches or in sixth place from the lowest. The Brinell of No. 2YB (yellow brass) is slightly higher than that for copper, but the drill penetration is twice as much, and the Brinell number for 187-A (an annealed leaded brass screw stock) is about the same as that for copper and No. 2YB, and yet the drill penetration is nearly four times that of copper. In other words, for the same Brinell number, the drill penetration varies for the different materials over a wide range. It is, therefore, obvious that the Brinell number by itself is no indication of the machining property of the nonferrous metals.

Power Required To Cut Metals

In order to make the machinability data of some practical value, the original data have been converted into horsepower required per cubic inch of metal cut per minute, as shown for the steels in Table V, and for the nonferrous metals in Table VI, for the planer tool, the ¾-inch drill, and the milling cutter. These values for steel are shown graphically in Fig. 48, the materials again being arranged in order of decreasing force or power on the planer tool. The Brinell numbers are shown at the top of the chart. It is seen that the drilling curve representing the horsepower per cubic inch of metal drilled per minute for the ¾-inch drill rotated at 152 revolutions per minute with a feed of 0.012 inches per revolution when cutting dry closely follows the similar curve for planing. The drilling value for S1 (a low carbon steel) is slightly low for its location, while those for 28 (S.A.E. 1020), 33 (die steel), and 31 (S.A.E. 3120) are high for their positions. Again it is seen that the steels having the highest power values, that is, the first four to the extreme left, are all straight carbon tool steels. The curve for the horsepower required to cut a cubic inch of metal per minute by milling is much higher than that for drilling and planing, averaging about three times the values for the two latter. The milling curve is also somewhat erratic, diverting for various metals from the drilling and planing curves. Also, inconsistencies are to be noted, such as for bar 29, which has a relatively high Brinell and a low milling horsepower value, as compared with bar 30, which has a medium Brinell number but a relatively high milling horsepower value.

The power required to cut metal is a function of the chip thickness. The power increases rapidly as the chip thickness is reduced below 0.020 inches.

The planing tool has an average chip thickness of 0.010 inches while the drill has an average chip thickness per tooth of the feed divided by two times the cosine of 31 degrees which gives 0.0055 inches. In milling the average chip thickness is much smaller, starting at zero and increasing to about 0.0037 inches which gives an average thickness of only 0.00195 inches.

The horsepower required to remove a cubic inch of metal per minute in planing, drilling, and milling may be compared with values given for grinding with modern precision cylindrical grinding machines of either centerless or control center type, as given by R. E. W. Harrison[2]. These values are the rates for metal removal which can be accomplished in a commercially practical manner.

H. P. Applied to the Grinding-Wheel Spindle	Metal-Removing Capacity, Cubic Inch per Minute, Cast Iron or Steel
5	½
10	1
15	1½
20	2
25	2½
30	3
35	3½
40	4

The horsepower per cubic inch of metal cut per minute for the nonferrous metals, as listed in Table VI, is shown plotted in Fig. 49. Here again the materials are arranged in order of decreasing force on the planer tool. The drilling power curves in Figs. 48 and 49 are slightly different from the torque curves as given in Figs. 46 and 47, because the thrust is included. The Brinell numbers for each material are shown plotted at the top of the figure. The horsepower in planing M (monel) is higher than that for N (nickel). The horsepower in drilling and milling, as well as the Brinell number for M, however, is less than that for N. With the exception of the Brinell number for copper, 50-A (unleaded brass), 187-A (leaded brass, annealed) which have low Brinell numbers, the Brinell curve has a tendency to slope from the left to the right, paralleling, in a general way, the planing power curve. Al-31 (aluminum) has a Brinell number which is above average for this range, but the power

[2]Engineering Director, Cincinnati Grinders, Inc., *American Machinist*, April 11, 1929, page 593.

curves for drilling and milling are both low. The Brinell number for GM (gun metal) also appears to be average for its position, but both the milling and drilling power values are high. It is, therefore, obvious that while the Brinell number may indicate, in a general way, the value of the milling, drilling, and planing power of a material, it is also true that the power curves are more uniform, that is, fluctuate less than the Brinell curve.

There is a great deal that can be added to the discussion of the data presented here. It might have been to advantage to have had the work-hardening capacity of each metal as determined by the Herbert pendulum. This device was not available, however, so that such data could not be included in this paper.

Chips of each material for each test have been preserved and an analysis of their makeup may help to explain many of the irregularities shown in the test data. Because of the limitation of time, this study must be deferred until later.

Conclusions

1. It may be stated that in general any one of the several methods of testing for machinability outlined above produce results which agree with those of the others. Tool life and finish of the cut surface are not included in these tests and no information is at hand to throw light on their relation to factors of power.

2. The force on a planer tool as an indication of the cutting qualities of a metal appears to be most reliable, as equal forces for like materials are consistently obtained. It is realized, however, that the equipment for this test is expensive and the execution of the tests is slow. No indication is obtained from the planer force for bar GM (gun metal) Fig. 47, that the drill penetration would be very low. Neither does the Brinell number indicate this.

3. The results obtained by measuring the torque on a drill while cutting offer good evidence as to the cutting qualities of the metal. The resulting thrust varies almost in direct proportion to the torque, so, by itself, offers an indication of the cutting resistance of the metal.

4. While consistent results may be obtained throughout a number of tests on a single specimen by the single-tooth milling cutter used in an impact type of machine, results from a number of steel specimens do not compare favorably with the results of other methods of tests on the same specimens. This may be due to the fact

that the cutting quality of these materials changes with the type of cut and thickness of chip. The milling cutter, for instance, does not cut to full depth at the start, but rather slides over the surface till enough pressure is developed between the material and cutting-tool edge to cause the edge to dig in. There appears to be no information available to explain the relation between such cutting action as a function of the chemical analysis of the specimen or its make up as influenced by heat treatment. The milling test is quick and inexpensive, however.

5. While the Brinell number is seen to vary almost directly with the Rockwell number and the ultimate strengths of the steel in tension, shear, and compression (Fig. 44 and Table III), its relation to the cutting force, energy, torque, thrust, or penetration of steel or nonferrous metals seems remote and in many instances entirely misleading.

6. The drill penetration test is simple, quick, and inexpensive to make. As a rule the greater the penetration in a given time or for a specific number of drill revolutions, the lower the power required than by any of the other methods of tests. There appears to be no uniform or constant relation, however. The difficulty of grinding the test drills makes this method very uncertain, particularly where the drill must be reground between one test and another.

Acknowledgements

These experiments have been carried out during the last two years in the Department of Engineering Shops of the University of Michigan. A limited amount of funds were made available by the Department of Engineering Research. These funds were not sufficient, however, to employ full-time experimenters, so that most of the work has been done by part-time employees and student assistants of the Department of Engineering Shops.

The writer wishes to express his appreciation to Professor A. E. White, Director of the Department of Engineering Research, through whose efforts the funds furnished by his department were raised, and for his continued interest in this work; to C. J. Swigert, who designed and built the planer dynamometer; to Fred Green, who assisted in the design and construction of the drill dynamometer; to Messrs. Irving I. Feldman, Giles V. Barr, and Harry A. Reed, who assisted in carrying out the various tests; to William Telfer, who supervised the hardness tests; to R. H. Harrington, who pre-

pared the photomicrographs; to Raymond V. Johnson, who assisted in making the tests and in working up the data; and to Mrs. Jessie Ferris, who assisted in the preparation of the final paper.

Some materials were furnished gratis by a number of different companies, among which were the Fredericksen Company, The International Nickel Company, The Scovill Manufacturing Company, The Dow Chemical Company, and The Universal Steel Company. Three types of steel and five nonferrous metals were originally prepared for a project of the Hardness Testing Committee of the American Society for Steel Treating, in which the object was to correlate the scratch tests with the other hardness tests and machining properties. The heat treating of the specimens and the determination of the machining properties were done by the writer; the hardness tests were made by G. R. Brown, Inspection Development Laboratory of the Western Electric Company; and the scratch tests were to have been made by Professor S. L. Goodale of the University of Pittsburgh. Through difficulties encountered in obtaining an instrument for making the scratch tests, the experiments were never completed and, for that reason, the results are not included with those originally intended for this paper.

DISCUSSION

Written Discussion: By A. L. Davis and W. N. Van Tassel, Scovill Mfg. Co., Waterbury, Conn.

This paper marks a further advance in our knowledge of this baffling subject. As in the case of fatigue endurance, the investigation of relative machinability of metals is one which requires a vast amount of work. In this field, O. W. Boston and E. G. Herbert of England are preeminent.

The following discussion is merely the presentation of Boston's results, after averaging the figures for similar specimens, and then expressing the results in the form of percentage.

We will consider the steels first. The results are set forth in Table I. The four samples of tool steel (2, 32, T1, T2) have been averaged together, as there was but little difference between them. The three samples of 0.15 per cent carbon steel have been averaged, likewise the two axle steels, and also the two so-called screw stock samples. The figures given are based on the power required to remove one cubic inch of material per minute, and have been reduced to a percentage basis, taking tool steel as 100 per cent. For the penetration test, reciprocals of the depth are reduced to percentage, based on tool steel =100. As a connecting link to Table II, the corresponding percentages for annealed copper are shown at the bottom of the table.

Table I shows the quite general agreement between the four different

Table I

Resistance of Steels to Machining

Relative H. P. Based on Tool Steel=100.

Proportionate power consumed (at nose of tool) to remove 1 cubic inch of material. Also Reciprocal Per Cent of Penetration of ¼ inch drill under fixed load.

Material	Planer	Drill	Miller	Resistance to Penetration
Tool Steel—Ave.	100.0	100.0	100.0	100.0
0.15 Carbon Steel—Ave.	89.5	85.7	86.0	70.8
S. A. E. 2345	78.3	79.2	65.9	74.0
S. A. E. 2320	75.0	74.1	90.3	81.3
Axle Steel—Ave.	75.0	75.3	74.0	72.2
0.30 Carbon Semi-Screw Stock—Ave.	74.8	70.4	50.5	61.0
S. A. E. 1020	73.8	84.2	70.0	67.3
0.65 Carbon 1.07 Cr. Die Steel	73.6	75.3	89.4	79.5
S. A. E. 3120	72.6	77.8	64.0	73.0
S. A. E. 1112—Cold Drawn	63.2	63.6	73.6	41.6
Cast Iron	43.8	43.2	36.6	30.1
Annealed Copper	80.3	129.6	65.8	44.8

methods of testing. It indicates the planer as the most reliable test, but shows torque-and-thrust of a standard drill a good second. Drill penetration under fixed load gives results which are fairly well in accord with those of the planer when used on steels. (As will be seen in Table II, the penetration test gives results which are widely divergent for some of the copper alloys). The milling test appears the least satisfactory. It should be borne in mind, however, that seeming inconsistencies in some tests by the miller and the penetration represent real divergencies that would doubtless be experienced in commercial machining operations of the same character as these tests. The objection to the miller and penetration tests is that they are not as fairly representative of usual commercial machining operations as are the planer and drill tests. In this connection it is of interest that production engineers have often claimed that steel must be annealed to one Brinell hardness to secure best machining on the lathe, and to another Brinell hardness for greatest ease in milling, and yet a third Brinell hardness to give best results for threading and tapping.

I am unable to establish any correlation between the physical properties as given, and the machinability for the steel series. Whilst generally it is true that high tensile, high Brinell (in annealed state) and high ductility (as measured by per cent reduction of area and per cent elongation), all go hand in hand with increased difficulty in machining, yet there are marked exceptions, e.g., S. A. E. 3120 would from its physical properties given be expected to machine with considerable difficulty; but the table shows it to machine as readily as any on the list except S. A. E. 1112. Possibly a full stress-strain diagram might throw light on the matter, though I doubt it. Probably the explanation lies in E. G. Herbert's finding that machinability is not determined by initial hardness, nor even by work hardening capacity, but predominantly by the property of building up on the nose of the cutting tool a semi-permanent tip, having the optimum angle for cutting. Small difference of internal structure of a metal may alter this angle of built-up tip, and so overshadow other more easily perceptible qualities when it comes to machinability.

It may be remarked in passing that none of the so-called screw stock steels tested is of correct analysis and tensile strength to give maximum free-cutting properties on automatic screw machines. It would be of interest to add tests of a modern super free-cutting steel, approximately 0.15 per cent carbon, 0.70 per cent manganese, 0.100 per cent phosphorus, 0.200 per cent sulphur, cold drawn to give 90,000 to 100,000 pounds per square inch tensile strength.

We come now to the nonferrous metals. Table II shows only the copper alloys. As in Table I, similar materials having concordant results have been averaged together. For example, the three sheet brass samples, and likewise two 15/16 inch diameter round brass rods. At the bottom of the table, the corresponding figures for tool steel have been added, to enable a comparison to be made. All figures are based on copper as 100 per cent.

Table II

Resistance of Copper Alloys to Machining

Relative H. P. Based on Copper=100.

Proportionate power consumed (at nose of tool) to remove 1 cubic inch of material. Also Reciprocal Per Cent of Penetration of ¼ inch drill under fixed load.

Material	Planer	Drill	Miller	Penetration	Analysis Per Cent Copper	Lead	Tin
Copper	100.0	100.0	100.0	100.0	100.0		
Annealed 50 Alloy	62.0	60.0	72.3	263.0	65.0	less than	
Manganese Bronze	40.0	46.2	49.7	407.0	55.0	.25	.75
Cast Red Bronze	33.0	21.6	33.3	33.8	80.0	7.50	3.00
Gun Metal	30.1	38.0	56.0	2670.0	90.0	none	10.00
½ Hard Sheet Brass	31.8	23.3	35.8	44.6	62.0	1.50	
Cast Yellow Bronze	29.8	20.0	47.0	51.1	70.0	2.00	1.00
Brass 1½ Hexagon Annealed	32.0	18.0	36.4	26.3	62.0	3.00	
Brass 1½ Hexagon Cold Drawn	30.3	17.6	38.3	29.5	62.0	3.00	
Hard Drawn Brass ½ sq.	30.2	17.0	40.1	28.7	62.0	3.00	
Brass Screw Stock 15/16 round	31.0	14.6	32.8	35.5	62.0	2.85	
Bearing Bronze "BB"	26.8	16.0	40.7	38.0	80.0	10.00	10.00
Bearing Bronze "5-SA"	20.2	12.1	24.9	19.1	70.0	25.00	5.00
Tool Steel	124.6	77.2	152.0	223.0			

Table II shows general agreement between the four methods of testing, barring three glaring exceptions with the penetration test. As with the steels, the planer test appears the most reliable. Next comes the drill, and then the milling cutter, with the penetration method last. Analyses of these copper alloys show the higher the copper content, the more difficult to machine, other elements remaining the same. The beneficial effect of lead is apparent. Lead is to brass what sulphur is to steel. The highly leaded brass screw stocks (A3, S3, and X) offer only about 1/6 the resistance to machining that copper does. This conclusion is in keeping with the ideas of industrial producers who have to machine such material.

One is naturally curious as to the explanation of the seemingly anomalous results of the penetration test on manganese bronze, gun metal, and annealed common high brass (No. 50 alloy). Several years ago we

made a large number of similar penetration tests, and came to the conclusion that these alloys tend to "load," or adhere, to the end of the drill, just back of the cutting edge. Also, penetration under fixed load may be influenced by the angle at which the chip shears away from the body of the metal being drilled. It is presumed that this angle of "shear" may vary from metal to metal, quite as E. G. Herbert has shown the angle varies of the false tip which builds up on the nose of a cutting tool.

As Boston points out, we do not know the relationship between power consumed per cubic inch of metal removed, and tool life (nor surface finish on the work). Production engineers are primarily interested in the cost of a given operation, which will be controlled by the output of a machine, under conditions which give a satisfactory finish, with reasonable tool life. Gaged by this standard, the output of an automatic screw machine is approximately twice as great when operated on free cutting brass screw stock as it is upon a free cutting steel screw stock. Let us note the relation between these two metals as shown by Boston's tests, and see how nearly they agree with this ratio of 2 to 1.

The ratio of S. A. E. 1112 steel to the free cutting brass rod varies somewhat according to the test employed. The planer gives a ratio of 2.6, the drill, 3.1, the miller, 3.2 and the penetration, 2.5, the average of the four being 2.85. It is possible that the sample of S. A. E. 1112 steel is not quite up to what we consider standard for free cutting screw stock.* If this be in fact the case, it would explain the ratio being 2.85 instead of about 2.0, which we believe to obtain in commercial machining.

Boston's work covers a wide range of testing methods, and great diversity of materials tested. It forms a necessary foundation and background for future investigation, which doubtless will aim to ascertain for a given metal and a given machining operation, what precise analysis and what heat treatment will yield optimum results. We desire to compliment Prof. Boston on this further contribution to the subject of machinability of metals.

Written Discussion: By F. G. Sefing, metallurgist, Michigan State College, East Lansing, Mich.

The paper is of high value in correlating the various types of machine operations. The graphs show up to better advantage, however, when the materials are arranged in order of decreasing drilling torque. Although this rearrangement does not alter the conclusions the curves become smoother, showing that the machining properties are even more closely related to each other than the author's curves seem to indicate. One conclusion which should have been emphasized is that the power required to remove a cubic inch of metal in one minute is a function of the drilling torque. It is indeed surprising how closely the power requirements are related to the drilling torque, so that we may predict with assurance the relative power cost to machine various metals.

*The specimen of S. A. E. steel 1112, which is supposed to be free cutting screw stock, was not analyzed so that we are not sure whether it fully comes up to the analytical specifications. Also the tensile strength is not given, so that we do not know that it was cold drawn sufficiently to give full free cutting properties.

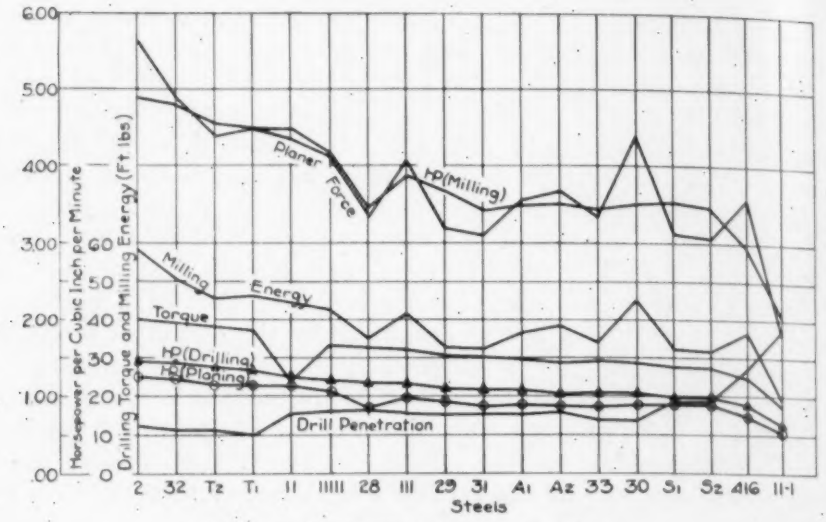


Fig. 1—Rearranged Curves for Steels.

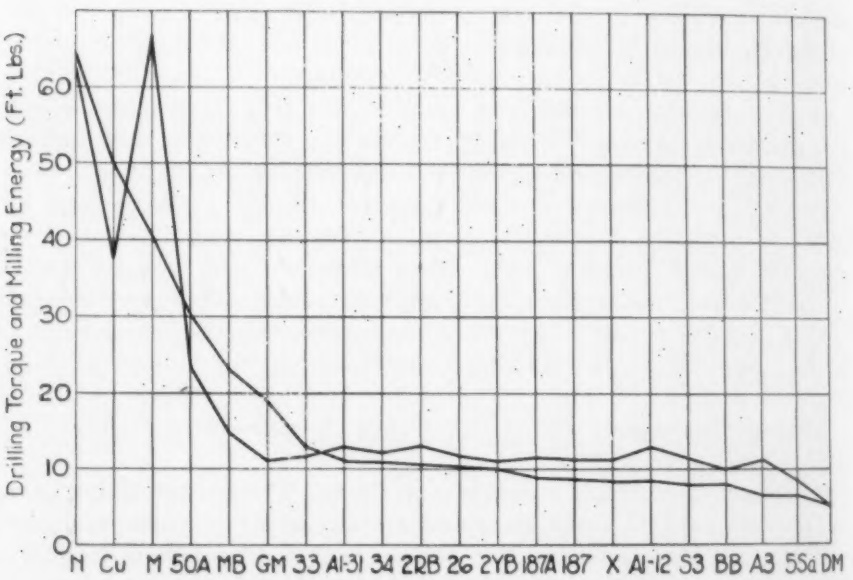


Fig. 2—Rearranged Curves for Nonferrous Metals.

It is arresting indeed that the physical properties indicated have so little relation to the machining properties. This merely signifies that resistance to machining is a property of metals which is separate and distinct from our common physical properties.

Written Discussion: By B. H. Blood, Hartford, Conn.

Prof. Boston's paper shows some very thorough work, so far as he has carried it, but suggests an extended field for continuing research when men and means are available. He has barely mentioned some of the variables which might be considered when the work is extended.

The shape of the cutting tool, and perhaps the cutting speed, for the different metals considered, might be expected to affect the comparative machinability ratings as shown in the paper. No one shape of tool and no one cutting speed can approach the optimum for such different metals as cast iron, steel, brass, copper, nickel and Monel metal. Since then many of the tests were made under conditions varying widely from good shop practice, further investigation based on the results obtained, but approaching more closely to practical conditions for each metal tested, seems promising.

The cost of power consumed in any machining operation is not of great moment, but when the power consumed can be used as an index of some other factor such as tool life it may be important to determine it. The horsepower required to remove a cubic inch per minute of the same metal with the same shape of tool might vary widely with tools of carbon steel, high speed steel and tungsten carbide, each operated at its optimum speed. This brings us to a consideration of the mechanics of chip formation, which is affected by speed and many other variables. In cast iron the chip is pushed off in chunks. In tough metals it is sheared or shaved off. The cutting speed and the shape of tool must be varied to get the best results. The work-hardening capacity of the metal cut has been shown to have a marked effect on the process of chip formation, and therefore on tool life, finish and power consumption, all of which are related to "machinability" if not included in the term.

Some of the inconsistencies between planer and drill results may be directly attributable to work-hardening. If we should use a drill shaped like a blunt cold-chisel we should have a good imitation of the action at the point of a twist drill. No true cutting action can result. The metal is pushed out of the way by brute force, and excessive cold-working results. If the metal is susceptible to work-hardening an excess thrust is developed. The rake of the cutting edge, the curl of the chip and the unit power consumed vary as we pass from the point to the periphery of the drill. In the planer tool we have more constant conditions.

In the milling cut we have another variable,—the depth of cut. All things considered, it is surprising that the results from the three methods of removing metal agree as well as they do. It is not uncommon in the shop to find certain metals which are difficult to mill, to drill or to thread, though turning or planing may offer no difficulty. This suggests the thought that the more constant conditions found on the planer may not be the ideal ones for determining machinability in its broad sense.

The announced object of the paper is "to indicate, if possible, the best method for determining whether or not the material is suitable for machining purposes." While this is highly desirable, so many factors enter into the term "machinability" as understood in the shop or in different shops that it seems hopeless to find any one test that will differentiate the various factors involved, and the test which will best integrate or average these factors, will probably require other tests for specific qualities. Some combination, such for instance as one of those used by Prof. Boston with

the Herbert work-hardening test, may prove to be reasonably simple and comprehensive.

I hope that means may be made available for Prof. Boston to continue his work, and that the discussion of his paper may assist him in selecting the most promising channels for it.

Written Discussion: By James A. Hall, professor of Mechanical Engineering, Brown University, Providence, R. I.

When Frederick W. Taylor and Carl G. Barth reduced the data of their metal cutting experiments to definite laws and applied them to slide rules, they used two machinability factors. One of these was a function of the life of the tool when cutting the given material, while the other was determined by the power required for this material and showed the maximum feeds that could be carried by the machine. This paper gives much valuable data concerning the latter type of machinability, and its figures for the nonferrous metals are of particular importance, as they vary more widely than the steels and less is known about them.

With so much of value in the paper it is unfortunate that the impression is left that several times as much power is required to remove metal by milling as by planing or drilling. An attempt to explain this discrepancy is apparently made on page 691 in the statement "The power (required by milling) increases rapidly as the chip thickness is reduced below .020 inch. The feed used in the tests was 0.010 inches per tooth. For the conditions assumed on page 684 of the paper, this is more than 8 inches per minute, which can hardly be considered unduly low for a 14 tooth cutter.

While this investigation indicates that three to five horsepower are required to remove one cubic inch of steel per minute, a common approximation used by milling machine manufacturers is one cubic inch of steel or two cubic inches of cast iron per minute for each horsepower of motor rating. This figure is a little high but should be attained for ordinary materials within the overload capacity of the machines, as shown by the following tests made at the plant of the Brown and Sharpe Mfg. Co.

Using a standard ten horsepower milling machine, 19.6 cubic inches of machinery steel were removed per minute with the motor overloaded 100 per cent. In another case the depth of cut in machinery steel was 0.125 inches, which is the same as that used in the machinability tests. A nine tooth cutter running at 68.5 revolutions per minute was used, and, although it was somewhat dull due to long use since the last grinding, the results were as given below. To make the figures directly comparable to the data of the paper, the feed is given in inches per tooth of cutter and the horsepower as the rate per cubic inch of steel per minute.

Feed per Tooth	Horsepower per cubic inch per minute
0.0022 inch	1.77
0.006 inch	1.47
0.0111 inch	1.30
0.0153 inch	1.22

Many other figures could be given to prove that the power actually required for milling is far below the results given in the paper even when relatively fine feeds are being used. As the former have been secured from work on standard machines, using stock milling cutters, and measuring the total power input, some question may be raised concerning the reliability of dynamometer tests for milling such as are reported in this paper.

Data concerning the pressures and powers developed in metal cutting is of great value both to those who are designing and to those who are laying out production on machine tools, and Prof. Boston has done a real service in making these investigations and in presenting such a large amount of information. In general, the writer believes that the results of the planing and drilling tests are correct, but he cannot accept the figures for milling. It is hoped that the closure of the discussion will include some estimate as to what extent the figures can be taken as absolute as distinct from comparative only.

Written Discussion: By T. G. Digges, U. S. Bureau of Standards, Washington, D. C.

Prof. Boston's paper is a valuable and interesting contribution to our knowledge of the fundamental factors that govern the machinability of ferrous and nonferrous materials. The results of his experiments indicated that the force on a planer tool while cutting was the most reliable indication of the cutting quality of the metal. If the cutting quality of the metal or machinability be measured in terms of the cutting force, does it follow that a material that has a low cutting force has a corresponding increase in tool life when subjected to roughing or finishing cuts or is such a material suitable for a thread cutting operation?

The speaker agrees that it is most desirable to correlate the various methods of testing machinability, but he does not believe that one method of testing will tell the whole story as to whether or not a metal is suitable for the various machining operations that are essential to modern shop practice. For example, it is a common experience to find a material that machines in a satisfactory manner when subjected to roughing cuts where the primary object is to remove the maximum amount of metal in the minimum time at the least cost and to find the same material unsuitable for a machining operation such as a finishing cut where a smooth surface finish is of more importance than tool life.

Many inquiries are received at the Bureau of Standards in regard to the machining of steels. These inquiries relate primarily to tool life and often to the finish on various classes of work with many types of tools. It seems as if this type of information is of considerable practical importance. Previous experiments have shown that empirical laws exist between the cutting speeds, feeds, depths of cut and tool life in cutting certain carbon and alloy steels with various types of tool steels under finishing or roughing conditions of service. It would be of considerable interest if Prof. Boston could correlate the results of some of his machinability experiments in terms of tool life.

Written Discussion: By H. L. Daasch, Metallurgist, Oliver Farm Equipment Co., Charles City, Iowa.

Data and information on the machining of metals is slowly being built up to make more possible a scientific understanding of the process; and this paper is, as have been others by the author, indicative of tedious and painstaking work.

If the author will pardon the liberty taken in handling his data, the accompanying curves and analysis are offered. Only plain carbon steels—numbers 2, 11, 111, 11111, 28, 32—on which complete physical data are given will be considered. It would seem more ideal to compare more or less similar steels. Coincidently, the alloy steels—numbers 29, 30, 31, and 33—are all mentioned some time or other by the author as being out of line when considering the data from one angle or another. This varying alloy effect is thus eliminated by considering only the carbon steels.

The author's system of plotting has been adopted and the steels arbitrarily arranged in the order of increasing Brinell number. The physical properties—tensile, compressive, and shear strengths, and elongation are plotted. Yield points follow maximum strengths quite closely and reduction of area is quite in proportion to elongation and are not plotted. The common parallel of Brinell and tensile strength, Brinell and compressive strength, less uniform correlation of Brinell and shear strength, and the more reciprocal Brinell-elongation relationship are indicated.

Machining horsepower curves plotted to coordinates so as to get uniform spread of curves are shown next as well as an average of these. For this group of steels, the close similarity of curves representing the three methods of power measurements warrants, it seems, a numerical average curve to smooth out possible experimental variations—if such be assumed to exist.

Curves showing products of (1) elongation and shear, (2) Brinell and shear, (3) elongation and Brinell, and (4) energy of rupture are also plotted.

The lack of correlation between machinability—machinability as used by the author—with hardness, tensile and compressive strengths, or elongation is evident. French and Digges similarly reported no correlation between ordinary tensile test factors or hardness values with their criterion of machinabilty which was cutting speed. However, there appears a trend when shearing strength is considered. Of the physical properties determined, the shearing strength seems most indicative of machinability as here tested.

Others, particularly Heyn, Kessner, and Grossmann, suggest that machinability depends on the combined effect of hardness and plasticity. There is, of course, lack of general agreement on the term machinability and absolute comparisons cannot be made. Yet Grossmann's conception of machinability and methods of measuring such are quite in line with those of the author. In accordance with this idea, the Brinell-elongation curve should parallel the machinability curve. Prof. Boston's results do not substantiate the hypothesis suggested—a hypothesis built up, as already

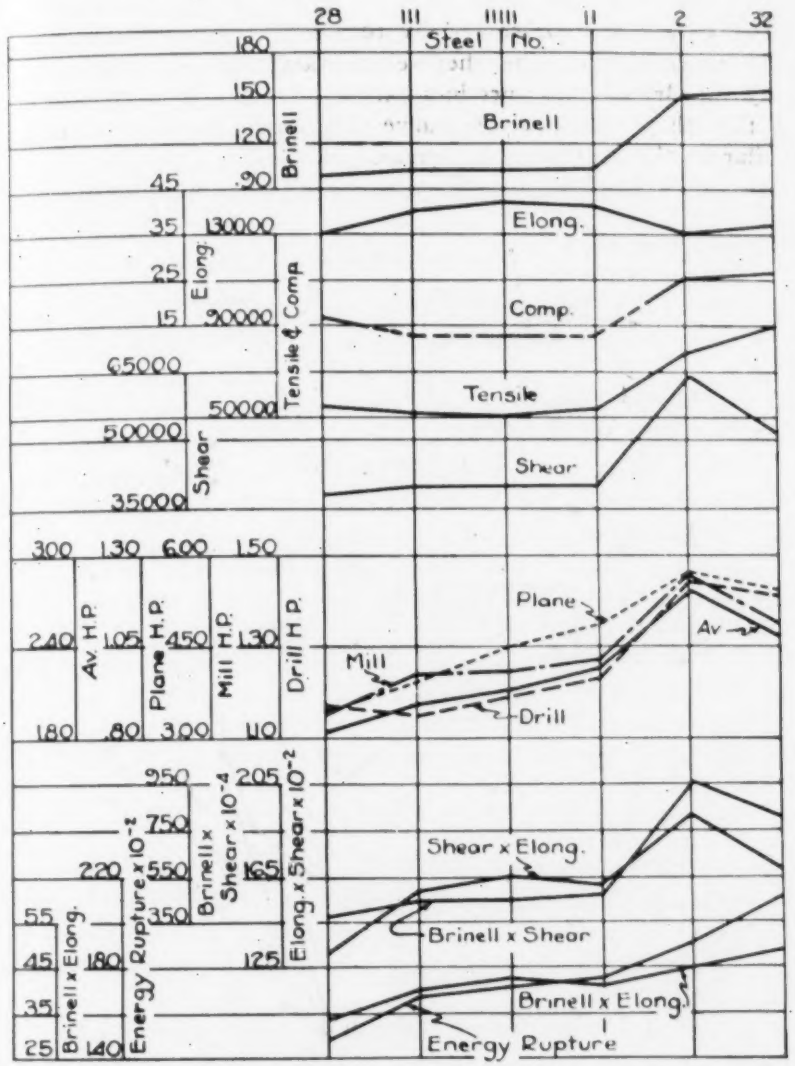


Fig. 1—Replotted Curves for Steels.

mentioned, on a definition of machinability and methods of measurement similar to those used by the author.

The energy of rupture as secured by tensile test values may be approximated by:

$$\text{Energy equals } \frac{(\text{Yield point} + 2\ \text{Maximum Tensile})}{3} \times \text{Elongation}$$

Examination of the curve showing this value would seem to show that the energy of machining is not indicated by the energy of rupture as calculated from tensile test values.

Because of the similarity of the machining horsepower and shear strength curve, and because of opinions of various students of the problem

that deformation as represented by tensile test elongation is probably a factor of machinability, the shear-elongation product curve was plotted. Similarly the Brinell-shear product curve is shown. It is striking and suggestive that the shear strength curve and curves incorporating this value are similar to the machinability curve.

Klopstock's four steps in his analysis of chip formation are: (1) in-

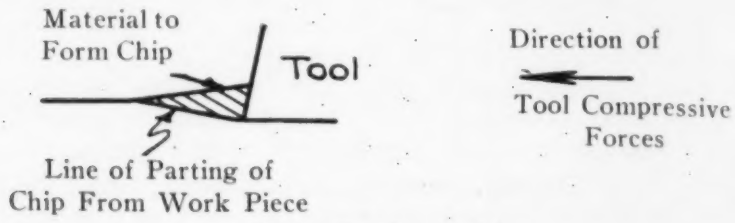


Fig. 1—Forming of Chip.

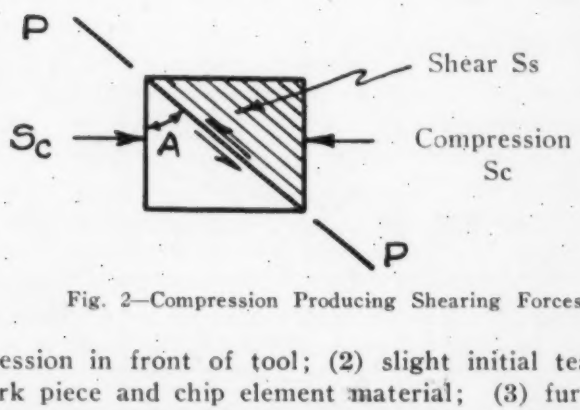


Fig. 2—Compression Producing Shearing Forces.

itial compression in front of tool; (2) slight initial tear between main part of work piece and chip element material; (3) further compression of chip element material and bulging on lip surface; and (4) then a tear between this material and the main work piece. Fig. 1 indicates roughly how the chip is formed.

Fig. 2 indicates how this mechanism of compression might result in active shearing forces.

Here the shaded section becomes analogous to the material which is to form the chip in Fig. 1.

It may be shown that:

> Maximum unit shear S_s equals ½ unit compressive stress S_c when angle A is 45 degrees.

Examination of the author's data will show in each case excepting steel number 2, that the ultimate shear strength is less than half the ultimate compressive strength. It would seem that parting along PP, Fig. 2, would be a shear phenomena and would occur before failure by compression in the case of the steels under consideration.

As applied to Fig. 1, chips would then be formed by shear along the line of parting caused by the tool compression. We may thus arrive at the conclusion that Klopstock's explanation of chip formation by com-

pression may actually result in material severance by shear—a possible condition roughly checked by the author's data on compressive and shear strengths and by comparison of machining horsepower and shear strengths.

The number of steels and the data here discussed are admittedly insufficient for rigorous conclusions. It is hoped that the author may secure further data along these lines and that the ideas here presented may stimulate thought along the channels suggested.

Oral Discussion

O. W. Ellis: This paper is a very valuable addition to what we know about the machinability of metals in general, and there are one or two points about it which are of great interest. In the table on page 679 for example, Prof. Boston brings out the very interesting fact, which has been observed before, that the leaded brasses are more readily machinable than the unleaded brasses. I would like to ask a question of Prof. Boston in this connection, because he may have done some work that would serve either to check or to confute certain of the work which I have carried out. Taking a series of brasses containing little or no lead, and testing them by means of a drill, in not quite so refined a way as that used by Prof. Boston, I found (1918) that there was a very definite relationship between copper content and machinability. We know that the commercial brasses may be divided into two groups, the alpha and the alpha-beta brasses. In the tests which I carried out, the drillings obtained in the case of the alpha brasses were continuous and there was a tendency for the drillings, when formed, because of their continuity, to block up the hole produced by drilling and thus to increase the resistance of the metal to penetration. It was not so much the fundamental character of the alloy, but rather the accumulation of material in the drilled hole, that accounted for the behavior of the material under test. When the beta constituent made its appearance in the alloys, the type of drilling obtained was different, probably because the beta constituent was brittle and, being brittle, caused the alpha crystals to break up on machining. This matter of the effect of structure on machinability is one that I should like to hear discussed by Prof. Boston if he has any information along that line.

Another point I should like to refer to in this connection, because it may be of interest to Prof. Boston in his further experiments. Consider, for example, such material as 60-40 brass. In a cold-rolled bar the alpha and beta constituents are arranged longitudinally, due to the methods by which the material has been produced. We found very definitely that in the case of material in which the crystals were arranged in a longitudinal direction, the machinability was much superior to that of materials in which the crystals were arranged in a haphazard manner. In the table already mentioned, Prof. Boston refers to brass screw stock and to brass screw stock annealed, and shows that the difference between the annealed and unannealed material is relatively small. I should like to see a similar experiment carried out with unleaded cold-rolled brass, testing the material first in the condition as received, in which the alpha and beta con-

stituents are distributed longitudinally along the bar, and testing the material after annealing when the alpha and beta materials are distributed in a haphazard manner.

This paper indicates very clearly how reliable Prof. Boston's testing equipment is. It would be interesting, with such reliable equipment, to get an answer to the two questions which naturally arise from the above discussion, and the speaker hopes that an answer may be forthcoming. We must congratulate ourselves upon the information that is being placed before us by the author and can only hope for more of such good work.

Author's Closure

B. H. Blood's discussion indicates clearly his wide knowledge of the subject of metal cutting and reflects his keen judgment in outlining problems for extended research. It is realized that each particular metal as well as each class of metals has probably a most efficient shape of tool and cutting speed for the least power, maximum tool life, and best finish. It is believed that no one shape of tool or cutting condition would prove best for each of the three factors, however. Such variations were purposely avoided in determining the results submitted in order that comparative results might be obtained, leaving the material as the only variable. The desirability of such tests as proposed were outlined in the paper under part 5 of the section on tests. Mr. Blood is looking far ahead when he suggests the use of optimum cutting conditions for each metal, as these conditions are not known for even the most common materials cut. To determine optimum cutting conditions for each metal is in itself a very large job, requiring a large variety of tool shapes, tool materials, cutting fluids and a vast quantity of the material to be cut. Some excellent work along this line was done by R. L. Templin of the Aluminum Company of America, for cutting aluminum (see Technical Publication No. 31 "Machining Aluminum," American Institute of Mining and Metallurgical Engineers, 1927). This covers cutting by drilling, turning, milling, sawing, etc. Similar results for other metals are not available in such a concise form, if at all, and often the optimum cutting conditions are left to the judgment of the machinist. Taylor, years ago, stated that his 22-degree side rake angle for cutting a soft steel might be increased still further, giving a reduction of power consumed and increased tool life. It is now known that some materials, or even some steels respond hardly at all in power reduction for an increase in rake angle, whereas with others the power is reduced almost in direct proportion to the increase in rake angle up to 45 degrees at an appreciable rate. It might be assumed that by increasing the rake angle, thereby reducing the force on the tool and the resulting power consumed, that the tool life would be increased. This, however, is not an established fact. The author believes that the force on the tool required to remove a cubic inch of a given metal would be the same whether the tool were made of carbon steel, high speed steel or tungsten carbide, each operated at its optimum speed, providing the tools were of the same geometric shape; the power then would vary directly

with the speed. Dr. Sauveur has shown that the physical properties of steels are reduced appreciably at temperatures above 300 to 400 degrees Cent., so that the high speeds permitted by the tungsten carbide tools may permit cutting above these temperatures. Tungsten carbide tools as well as stellite tools must, however, perhaps unfortunately, be ground to shapes and angles which differ from those for high speed steel tools. These questions are still to be solved in the building up of a science of metal cutting.

Mr. Blood's suggestion that some correlation might be found between these various metal cutting processes and the Herbert work-hardening tests, permits me to report in a forthcoming paper on the subject of drilling that such tests were made with negative results.

The author is intensely interested in the analysis made of the experimental data by H. L. Daasch. Mr. Daasch's product curves are extremely valuable, and while the shear-elongation curve follows closely the machinability curves, the author rather expected that the energy of rupture curve would follow it even better. This latter curve appears to be very satisfactory except for the last material, steel 32. The fact that the force on the planer tool is much greater than the ultimate strength of the material in tension, compression, and shear combined, indicates that there is something more happening to the material during the cutting process. Mr. Daasch's analysis of chip formation appears to be more appropriate for materials such as cast iron and brass which shear off, rather than for the steels which usually tear, shear and flow. In his Fig. 1, is illustrated the shear type chip. However, for the steels, a small built-up cutting-edge on the face of the tool causes the ductile materials, particularly with heavy cuts, to tear ahead of the cutting edge, but parallel to the outside of the work. This prepares the chip in the form of a ribbon which is later sheared to a laminated structure as it is pressed against the face of the tool.

The analyses of the data given by Messrs. A. L. Davis and M. N. Van Tassel are also illuminating, and show up perhaps better than in the form presented by the author the close relationship existing between the various metal cutting processes. They have been a little more bold than I dared be in taking averages of tests for materials of like chemical analysis. The grouping of the high-carbon tool steels seems quite appropriate due to the uniformity of results, but low-carbon steels, for some reason or another, seem to give greater variations in test results.

The comments of T. J. Digges are quite appropriate. There appears to be no scientific information available which correlates power, tool life, and finish for a given material and tool. The author purposely omitted the subject of tool life and finish because of the tremendous amount of work and expense involved. It is unfortunate that so many investigations are conducted along particular lines by various individuals or industries, the results of which are not correlated with the work of others. The mere fact that we do not know the correlation between power, tool life and finish in spite of the tremendous amount of metal being cut daily, is la-

mentable. The author believes that these three factors are independent, that is, a given material has a certain structure for lowest power consumption, another for greatest tool life, and a third for best finish. Even this would have to be correlated with a tool particularly suited for each purpose.

O. W. Ellis raises the interesting question as to the difference of chip formation between the alpha brass and the alpha plus beta brass. Chips from every test and material have been retained and the author agrees substantially with Mr. Ellis in that for the unleaded brasses the chips were in most instances continuous. For the drill penetration tests that gave the finest chips, brass bar No. 26 gave many helical chips one inch in length. Brass bar No. 33 gave chips less continuous and, in most cases, consisted of one or two turns of the helix. Brass bar No. 34 also gave many continuous chips the length of which varied from ¼ to ¾ of an inch. The leaded brasses A3 and S3 and X all gave chips the length of which were all less than ½ revolution, and all of which were much finer than the unleaded brasses. The drill penetration tests on brass RB 2 also were finely broken up, most of them being about one turn of the helix. Manganese bronze, on the other hand, gave very thin, but in the main, continuous chips.

The chips from the milling machine showed more uniformity in size and make-up for all of the brasses. On the planer, however, the chips from brass bars No. 26, 33 and 34, of the unleaded type, were all continuous coils averaging ½ to ⅝ of an inch in diameter. Bar No. 33, however, gave chips slightly larger in diameter with fewer turns and were of a more brittle appearance. Bar A-50 gave chips in the form of a spiral approximately 1½ inches outside diameter. The leaded brass 187-A gave spiral chips about ½ inch outside diameter which were continuous; whereas bar 187 gave chips which were well broken up into lengths not exceeding ⅛ of an inch. Leaded bars A3 and S3 also gave chips which were broken up, but more continuous than those of 187. The leaded bar X gave rather continuous chips in coils not exceeding ½ inch in diameter nor more than two complete turns. Bar GM gave planer chips of about ½ turn, having a radius of ¼ inch. Bar No. 5 Sa gave broken-up chips usually in the form of a spiral coil less than ¼ inch in diameter. BB gave chips well broken up. MB gave ribbon-like chips, the various thread-like laminations of which were completely separated from one another. Copper, on the other hand, gave a chip rather straight, consisting of the whole length of cut, burnished on the bottom and showing a laminated structure on the upper part.

I have no information to offer Mr. Ellis as to his second point regarding the machining properties based on the arrangement of the particles. In all of my tests, the bar was cut lengthwise on the planer and miller, but crosswise in both types of drilling. I have, however, noticed that different results in drilling torque are obtained when drilling steel screw stock transversely or longitudinally.

It seems particularly appropriate that Prof. Hall has raised the ques-

tion as to absolute or comparative values of the data presented in the paper, so that a word of caution may be given. It must be remembered that the object of the paper was to secure, by different machining methods, data for each material which could be compared directly with data from other materials. Machinability data was reduced to horsepower per cubic inch of metal removed per minute for each type of cut, to make them of general commercial value. The specific conditions for each type of cutting, however, must be borne in mind. It is known positively that if the feed used on the planer tool had been greater than 0.010 inches, the horsepower per cubic inch of metal removed per minute would have been less than those given. Also, if the feed had been less, the values would have been greater. The same holds true for drilling; that is, the values given represent the power per cubic inch of metal cut per minute for the ¾-inch drill operating at a feed of 0.012 inches per revolution, and a speed of 153 revolutions per minute. If the drill size or shape were varied, or if any of the other cutting conditions other than speed were varied, the horsepower values would be different. It is true, as Prof. Hall points out, that the power required to cut the metals by milling is much higher than by planing or drilling. This is unfortunate, perhaps, unless one is mindful of the specific conditions. The milling machine was small and therefore cuts within its capacity had to be maintained. The fact that one cubic inch of steel, or two cubic inches of cast iron per minute for each horsepower of motor rating are values used as a common approximation by milling machine manufacturers, without any stipulation as to the type of steel, its structure, the shape or size of the tool, the shape and size of cut, etc., indicates of course, that these values are only very general approximations and may be in error by 200 or 300 per cent. To illustrate, suppose the designers of drilling machines assumed the above values for drilling. H. M. Norris* shows that when drilling with drills ranging from ½ inch to 1½ inches at ¼ inch steps, with a feed of 0.0155, the horsepower per cubic inch per minute for the various drill sizes is as follows:

1½ Inch diameter = 0.8
1¼ Inch diameter = 0.94
1 Inch diameter = 1.05
¾ Inch diameter = 1.44
½ Inch diameter = 2.25

These power values would increase rapidly as the feed is reduced. The point to be noted is the variation in horsepower per cubic inch of metal cut per minute from 0.8 to 2.25, an increase of 180 per cent. This range would be considerably increased if the feeds were reduced.

In answer to Prof. Hall's question as to what extent the milling values given can be taken as absolute as distinct from comparative, it may be stated that they are comparative as all tests were taken under the same conditions, and they are believed to be absolute within reasonable limits

*"Power Absorbed in Drilling Various Metals at Various Speeds and Feeds," *American Machinist*, Vol. 27, part 1, 1904, p. 74.

for the specific conditions outlined. Unfortunately, Prof. Hall has not given enough information as to the specific cutting conditions to make an analysis possible of his two illustrations of horsepower required to cut a cubic inch of machine steel per minute. One should be able to determine the average thickness of chip for which the diameter of the cutter is needed.

It is not stated whether it is the plane or side type of cutter, and whether the cuts were wet or dry. Neither is the front-rake angle of the teeth given. The author's milling machine was an impact type of machine using a single-tooth side cutter having a 1¾-inch radius, cutting in a groove ⅛ inch deep. This cutter had a 15-degree front-rake angle and the cuts were made dry. The high values of horsepower per cubic inch of metal per minute in milling are justified for the following reasons: previous experiments show that with a ½-inch wide planer tool, otherwise similar to the milling cutter, 24 per cent increase in power is required when the tool cuts in a groove as compared to cutting on a land. If the cutter width is reduced ¼ inch, it is estimated that this percentage increase would rise to 50 per cent. The fact that each chip was taken at comparatively long intervals, would mean that the material cut would be at room temperature so that between 10 and 25 per cent more energy would be required. This is based on the value of Brinell readings under somewhat similar conditions. While this conjecture may account for the high values of the milling horsepower, it is realized that this is but one of many problems upon which further test data is needed.

F. G. Sefing's comments are interesting and the author is glad to have presented the test data arranged in order of reducing drill torque for comparative purposes. This arrangement was first tried out by the author, but it was felt that the planer force, being the simplest type of cutting, gave the best all around arrangement.

The author is, indeed, grateful for the interest shown by those entering the discussion and extends his thanks to those who have brought out various points pertinent to the subject which make the paper of more interest and value.

HOT AQUEOUS SOLUTIONS FOR THE QUENCHING OF STEELS

By H. J. French and T. E. Hamill

Abstract

Surface and center cooling curves are given for small cylinders of high carbon steel quenched in water, sodium hydroxide, sodium chloride solutions and oils at different temperatures. The characteristics of these cooling curves and a study of the hardnesses and structures produced suggested the possibility of using some of the hot aqueous solutions to bridge the gap between the cooling rates obtained with water and oils at atmospheric temperatures. Experiments with carbon and alloy steel tensile test specimens and gages seemed to justify the view that hot aqueous solutions can provide a useful group of coolants with graded cooling characteristics for the hardening of small steel pieces. Suggestions for further work are also given.

I. Introduction

THE experiments described in this report relate to the effect of temperature on the cooling properties of liquids widely used in the hardening of steels and comprise part of a general study of quenching which has been in progress for some time. The results previously reported have related to the properties and structures produced in carbon steels by different coolants at ordinary temperatures,[1] the effects of initial temperature and mass on center cooling,[2] the characteristics of center cooling curves,[3] and a study of the sur-

[1]H. J. French and O. Z. Klopsch, "Quenching Diagrams for Carbon Steels in Relation to Some Quenching Media for Heat Treatment", Transactions, American Society for Steel Treating, Vol. 3, 1924, p. 251.

[2]H. J. French and O. Z. Klopsch, "Initial Temperature and Mass Effects in Quenching". Technologic Paper of the Bureau of Standards, No. 295; Transactions, American Society for Steel Treating, Vol. 9, 1926, p. 33.

[3]H. J. French and O. Z. Klopsch, "Characteristics of Quenching Curves". Technologic Paper of the Bureau of Standards, No. 313.

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A paper presented before the Eleventh Annual Convention of the society, Cleveland, September 9 to 13, 1929. The authors are members of the society. H. J. French, formerly senior metallurgist, U. S. Bureau of Standards, is now associated with the International Nickel Co., T. E. Hamill is junior metallurgist, U. S. Bureau of Standards, Washington, D. C. Manuscript received May 23, 1929.

face cooling of steels in quenching[4] but little attention was given in these investigations to the effects of coolant temperatures on the manner of cooling or the properties of the quenched steels.

This subject is of interest from several points of view. More information than is now available might point the way to further useful applications of different liquids, and should help to establish the limits within which coolant temperatures should be controlled for uniform results; it should also serve to place the time-temperature relations, when quenching steels in hot liquids, upon a firmer foundation.

It is true that much is already known of the effects of temperature upon the coolants now ordinarily used in commercial heat treatment but this information is of a general nature and based largely upon the properties and structures produced in different steels and the cooling characteristics at the interior of metal bodies. Quantitative information is lacking on the manner of cooling at the surfaces of steel bodies immersed in liquids at different temperatures, and it is the purpose of this report to present such data and a correlation of surface and center cooling with the properties and structures produced in steels.

As early as 1873, Caron[5] used water at 55 degrees Cent. for the quenching of steel springs for hair-triggers in rifles and obtained quite as good results as those obtained by more energetic quenching followed by tempering. He also used boiling water for the quenching of 0.2 to 0.4 per cent carbon steels to increase their tensile strength without altering their hardness.

II. Methods of Test Used

The experimental methods already described[6] were used in the tests and the steel cylinders, ½ inch in diameter and 2 inches in length, were all quenched from 875 degrees Cent. (1605 degrees Fahr.) into coolants moving at 3 feet per second. The test cylinders were made of 0.96 per cent carbon steel having the chemical composition reported in Table I.

[4] H. J. French, G. S. Cook and T. E. Hamill, "Surface Cooling of Steels in Quenching". Transactions, American Society for Steel Treating, Vol. 15, 1929, p. 217.

[5] E. Hitzel, "Tempering by Warm Water and the Works of Lieutenant-Colonel Caron", *Revue de Metallurgie Memoires*, Vol. 12, 1915, p. 584.

[6] See foot notes (1) and (4).

Table I
Chemical Composition of the Test Cylinders (Steel C41)

	Per Cent
Carbon	0.96
Manganese	0.28
Phosphorus	0.016
Sulphur	0.028
Silicon	0.18

Washington city tap water was used in the water quenching baths and in the preparation of the sodium chloride brines and the sodium hydroxide solutions. The two latter solutions were made respectively, with ordinary table salt and technical sodium hydroxide, containing 96 per cent NaOH, 2 per cent Na_2CO_3, 2 per cent NaCl, and 2 per cent moisture. The concentrations referred to in this report are weight percentages and the quenching was carried out in freshly prepared solutions.

Oil No. 2, which was used in a majority of the oil quenching experiments, is a proprietary product and the same oil which was used in earlier experiments.[7] Its properties were approximately as follows: specific gravity at 15 degrees Cent., 0.874; flash point, 190 degrees Cent. (375 degrees Fahr.); fire point, 212 degrees Cent. (415 degrees Fahr.); initial boiling point, 375 degrees Cent. (707 degrees Fahr.); final boiling point, which is the equilibrium boiling temperature as determined in a reflux flask under atmospheric pressure, 375 degrees Cent. (707 degrees Fahr.); and final vapor temperature in the determination of the boiling points, 345 degrees Cent. (653 degrees Fahr.). The exact composition of this oil is not now known but analysis indicated that it is probably a mixture of a naphthene base (mineral) oil and about 3.3 per cent fatty oil.

Oil No. 1 is another proprietary quenching oil and its selection for a few experiments was due to its reported ability to cause rapid cooling at high temperatures. This oil consists of a mixture of a small amount of a heavy Pennsylvania residuum oil of high flash point with a special distilled Pennsylvania stock of low flash point. Its properties were as follows: specific gravity at 15 degrees Cent., 0.867; flash point, 193 degrees Cent. (380 degrees Fahr.); fire point, 216 degrees Cent. (420 degrees Fahr.); initial and final boiling points (reflux method), 380 degrees Cent. (716 degrees Fahr.); final

[7] See foot note (1).

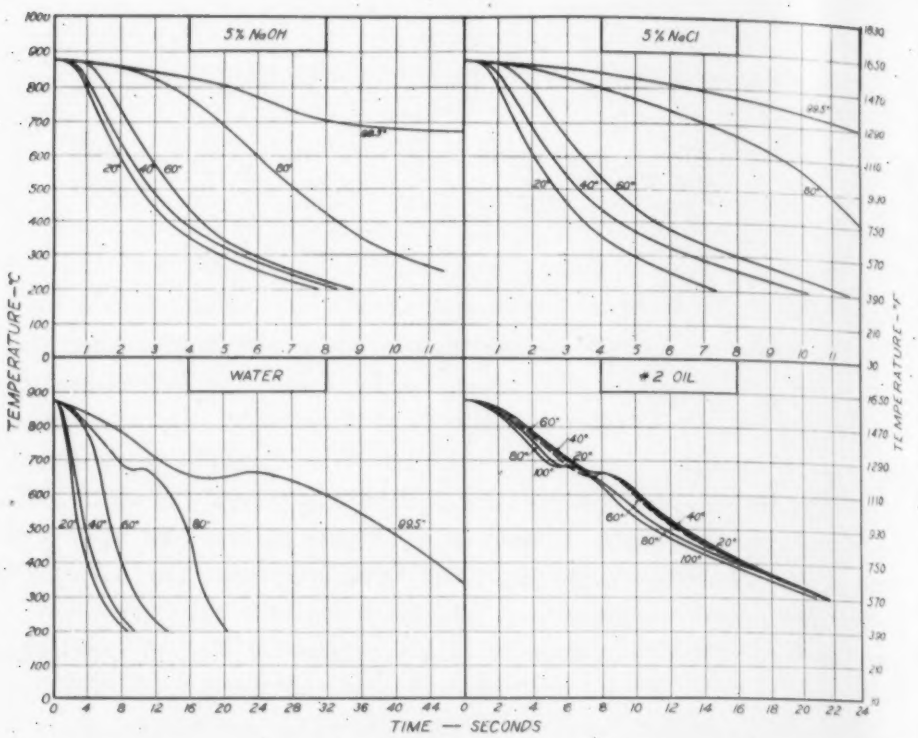

Fig. 1—Center Cooling Curves of 0.96 Per Cent Carbon Steel Cylinders Quenched from 875 Degrees Cent. (1605 Degrees Fahr.) into Liquids at Different Temperatures. Coolant Motion was 3 Feet per Second; Cylinders were ½ inch Diameter by 2 Inches Long. Each Curve is the Average of Two or Three Tests.

vapor temperature in the determination of the boiling points, 355 degrees Cent. (670 degrees Fahr.).

The reported values of hardness for the surfaces of the quenched cylinders are based on ten tests along the length of the cylinder in the area meeting the direct flow of the liquid. The tests were made after removing about 0.005 inch of the metal from the surface by wet grinding to form narrow flat bands along the length of the cylinders. Center hardness was determined from three tests after cutting the cylinders in half under water spray.

III. Results of the Tests

1. Center and Surface Cooling Curves

Figs. 1, 2 and 3 show the center and surface cooling of the steel cylinders immersed in water, No. 2 oil, 5 per cent sodium hydroxide and 5 per cent sodium chloride solutions at temperatures

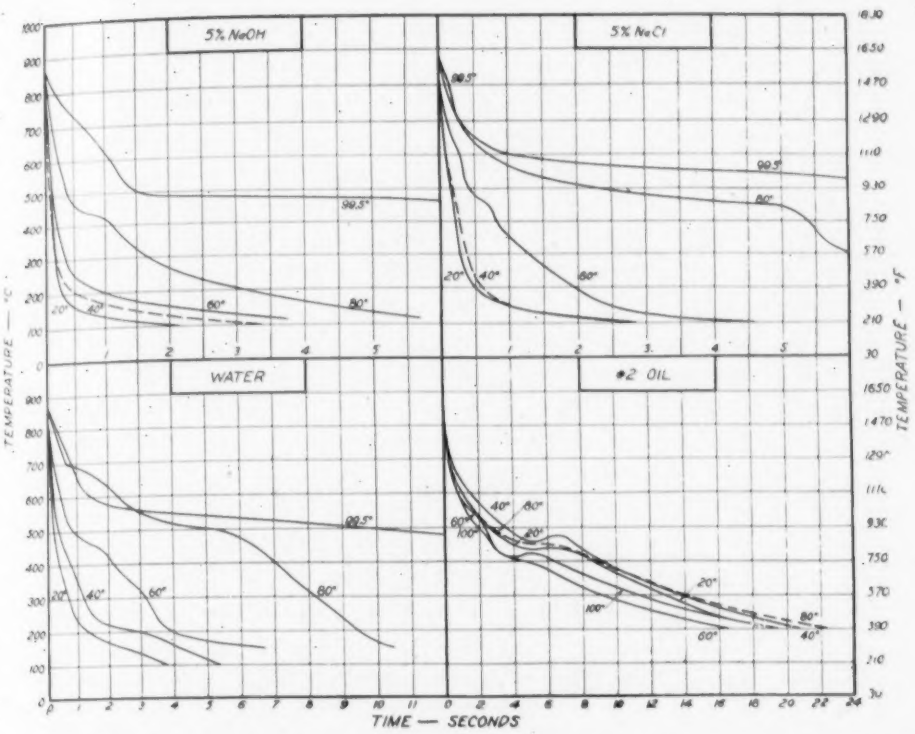

Fig. 2—Surface Cooling Curves of 0.96 Per Cent Carbon Steel Cylinders Quenched from 875 Degrees Cent. (1605 Degrees Fahr.) into Liquids at Different Temperatures. Coolant Motion was 3 Feet per Second; Cylinders were ½ Inch Diameter by 2 Inches Long. Each Curve is the Average of Two or Three Tests at a Point Meeting the Direct Flow of the Liquid.

between 20 and approximately 100 degrees Cent. Data for the No. 1 oil are given in Fig. 9.

The highest coolant temperature, for water and the aqueous solutions, is given as 99.5 degrees Cent. The practice employed was to heat the bath to 100 degrees Cent., then remove the source of heat, and transfer the tank containing the heated liquid to the quenching apparatus described in reports already referred to. Based on observations with the water baths, it was assumed that the average temperature drop in handling the different aqueous solutions was 0.5 degree Cent., and the specified temperature, 99.5 degrees Cent., merely indicates that the coolant temperature was slightly below the boiling point of water.

Figs. 1, 2, 3, 4 and 9 show that increase in the temperature lowered the cooling rates and increased the cooling times in water and the two aqueous solutions while opposite effects were produced in the center cooling by the two oils. The changes were small in the oils throughout the entire temperature range studied, (20 to 100

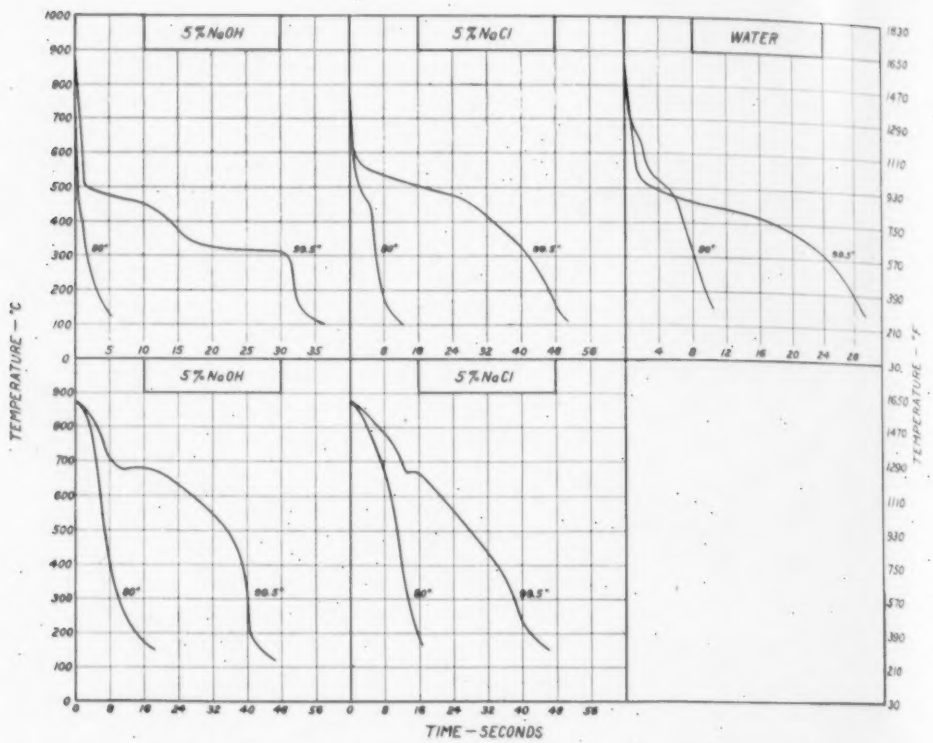

Fig. 3—Replot of Center and Surface Cooling Curves in Liquids at 80 and 99.5 Degrees Cent. (175 and 210 Degrees Fahr.) Shown in Part in Figs. 1 and 2. Surface Cooling Shown in Top Row, Center Cooling in Bottom Row.

degrees Cent.) and were not as marked between 20 and 60 degrees Cent. in the water and aqueous solutions as between 60 and 99.5 degrees Cent. Also, the changes in cooling times with increase in the coolant temperature were smaller in 5 per cent sodium hydroxide than in 5 per cent sodium chloride and, with the exception of the range 80 to 99.5 degrees Cent. were smaller in 5 per cent sodium chloride than in tap water (Fig. 4).

The fact that temperature increase of the coolant affects the cooling in 5 per cent sodium hydroxide somewhat less than in water may be of distinct advantage in practical heat treatment and probably contributes in an appreciable degree to the rapidity of cooling in the sodium hydroxide solution. In all quenching operations, the liquid adjacent to the heated steel is raised in temperature even though it is only momentarily in contact with the heated metal surfaces. At least a part of the cooling of the steel is effected through contact with heated liquid and the vapors formed by, or released from it.

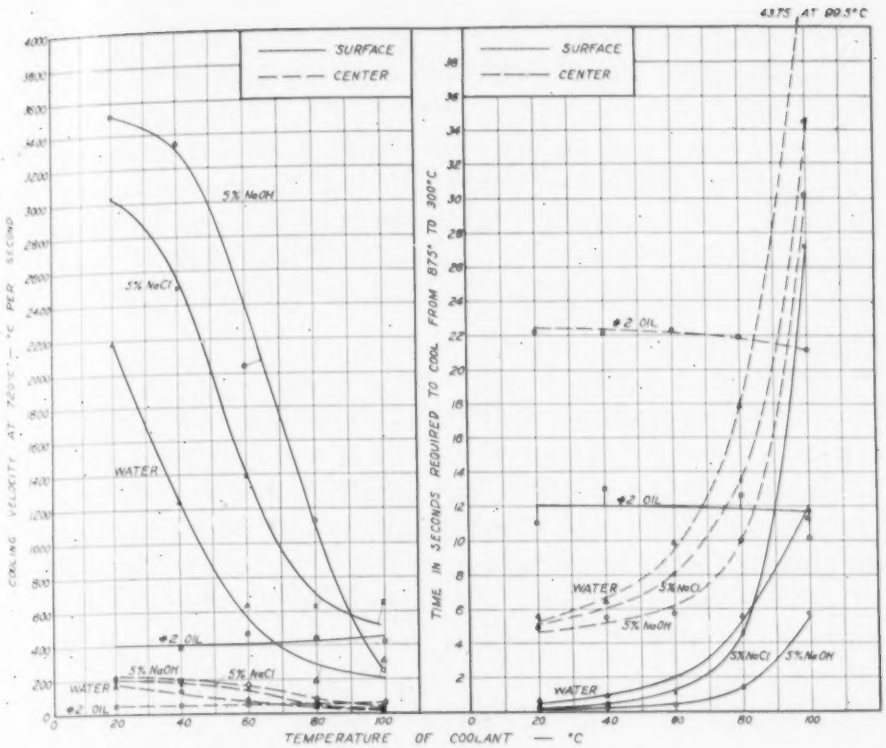

Fig. 4—Effect of Temperature on Center and Surface Cooling Times and Rates in Different Liquids. This is a Summary of the Curves Shown in Figs 1, 2 and 3.

In liquids which normally decrease in cooling speeds with rise in temperature, a small temperature effect, as in the sodium hydroxide, means a tendency to maintain rapid cooling as well as ability to compensate for deficiencies in circulation which usually tend to raise the effective temperature of the quenching bath. From this viewpoint, the 5 per cent sodium hydroxide is a more desirable coolant than water.

Figs. 1 and 3 show that the center cooling of specimens immersed in water at 80 degrees or 99.5 degrees Cent. was somewhat more rapid at low temperatures around 200 to 300 degrees Cent. (390 to 570 degrees Fahr.) than at high temperatures around 700 to 800 degrees Cent. (1290 to 1470 degrees Fahr.). A similar condition was observed in 5 per cent sodium hydroxide at 99.5 degrees Cent. but not at 80 degrees Cent. nor in 5 per cent sodium chloride at 80 or 99.5 degrees Cent.; in the last three cases, the cooling rates were quite regular throughout the temperature range, 850 to 200 degrees Cent. (1560 to 390 degrees Fahr.). In general, these center cooling characteristics were a reflection of the conditions at the sur-

face although the surface cooling became somewhat more irregular as the temperature of the aqueous solutions approached the boiling point of water.

Rapid cooling of the steel specimens at low temperatures in hot water and the hot aqueous solutions is well recognized and is usually considered to be disadvantageous since steels are least able to deform without cracking at temperatures around 300 degrees Cent. (570 degrees Fahr.) and so relieve the stresses accompanying the volume changes in hardening.

However, it is difficult to see how the rapid cooling in hot water could, by itself, cause great difficulty since the cooling rates are less than those obtaining in cold water, cold brines and sodium hydroxide solutions in which such difficulties are not important enough to prohibit their use in practical heat treatment. It seems more probable that the danger of cracking in hot water quenching is due to *lack of uniform conditions over the surface of the steel* during fairly rapid cooling at low temperatures. Evidence of non-uniformity was shown in the original records of the cooling curves, but a much better picture of this situation was obtained by watching and listening to the actual quenching operation.

As the initial temperature of the water bath is increased, somewhat less heat must be taken from the steel to form steam, and it is not unreasonable to assume that more steam will come in contact with, or become attached to, the surfaces of the metal in a given time. As has already been shown[8] such conditions promote non-uniform cooling since the action at the contact surfaces between the metal and the coolant, or their products, is probably made up primarily of rapidly repeated cycles of steam generation, momentary attachment of steam to the metal surface and its removal.

In any case, hot water at temperatures in the neighborhood of 80 to 100 degrees Cent. is not a good quenching medium under ordinary conditions. Where somewhat slower cooling is desired than can be secured in water at 20 degrees Cent. and the oils are too slow, possibilities may be found in hot brines and, more particularly, in the hot sodium hydroxide solutions. The center cooling curves were generally smooth, without abrupt changes in direction, for water at 40 degrees Cent. and 5 per cent sodium hydroxide at 60 to 80 degrees Cent. Also cooling times were obtained in the hot sodium hy-

[8]See foot note (4).

Table II

Comparisons of Hot Water or Hot Aqueous Solutions with Oils at Atmospheric Temperatures in Cooling High Carbon Steel Cylinders from 875 Degrees Cent. (1605 Degrees Fahr.)

Coolant	Approximate time, in seconds, to cool from 875°C (1605°F) to designated temperature (1)					
	800°C 1470°F	700°C 1290°F	600°C 1110°F	500°C 930°F	400°C 750°F	200°C 390°F
			At Center			
Water at 20°C	1.4	2.0	2.6	3.2	4.1	8.6
5% NaOH at 60°C	1.6	2.2	2.8	3.5	4.3	8.8
Water at 40°C	1.6	2.3	3.0	3.9	4.8	9.4
5% NaCl at 60°C	2.0	2.8	3.5	4.4	5.5	11.8
5% NaOH at 80°C	3.4	4.8	6.0	7.1	8.3	14.1
No. 1 oil at 20°C	2.9	4.9	7.5	11.1	15.6	28.8
5% NaCl at 80°C	3.9	7.1	9.4	10.9	12.1	16.0
No. 2 oil at 20°C	3.6	6.2	8.8	12.4	16.5	29.7
			At Surface			
Water at 20°C	0.02	0.07	0.12	0.21	0.38	1.2
5% NaOH at 60°C	0.03	0.08	0.11	0.15	0.24	1.0
Water at 40°C	0.06	0.14	0.22	0.34	0.56	2.0
5% NaCl at 60°C	0.03	0.11	0.22	0.38	0.62	1.8
5% NaOH at 80°C	0.07	0.15	0.25	0.40	0.72	3.1
No. 1 oil at 20°C	0.07	0.15	0.34	0.96	2.5	14.7
5% NaCl at 80°C	0.10	0.30	0.70	1.48	2.78	7.0
No. 2 oil at 20°C	0.09	0.27	0.89	2.4	5.5	19.3

(1) Heat effects of transformations disregarded.

droxide solutions which were between water and oils at ordinary temperatures, as is shown in Table II.

In examining the data in Table II, it should be kept in mind that the cooling curves obtained in aqueous solutions have a somewhat different form than those in the oils, and for this reason short cooling times at high temperatures are not necessarily concomitant with short cooling times to low temperatures. The cooling at low temperatures in oils is generally slower than that in aqueous solutions as is shown in Figs. 1, 2, and 3, and Table II, and the temperature of the coolant which may give the desired results will depend upon the steel under treatment, its size and shape, etc.

2. *Hardness and Structures Produced by the Different Coolants*

The effects of temperature of the coolant on the hardness and structures produced in the ½-inch diameter by 2-inch cylinders of 0.96 per cent carbon steel are shown, together with cooling times, in Figs. 5 to 9 inclusive. Fig. 10 contains direct comparisons of the Rockwell hardness produced by quenching in the different liquids at different temperatures.

The fully hardened 0.96 per cent carbon steel, having a martensitic structure free from readily detectable areas of troostite, had

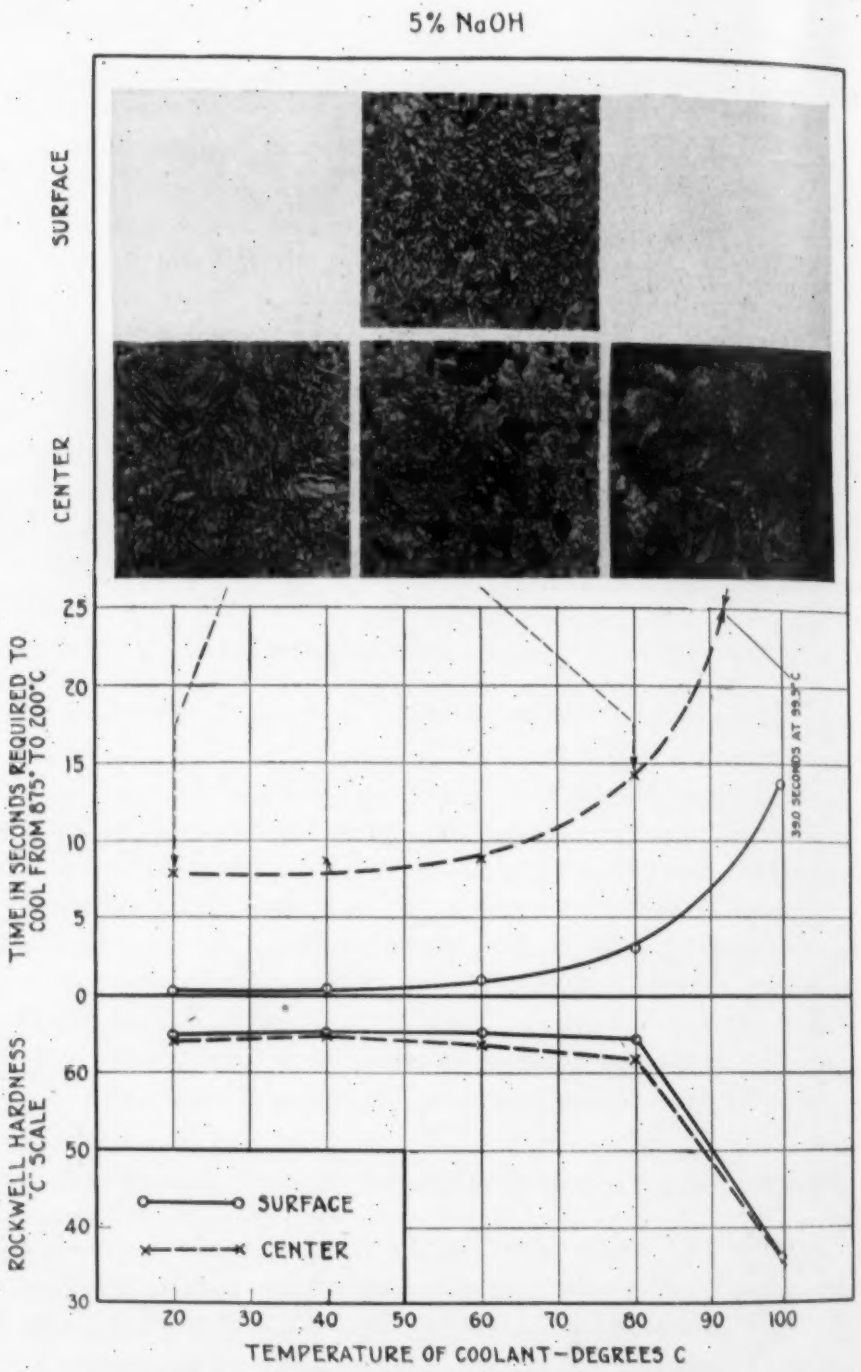

Fig. 5—Hardness, Cooling Times and Structure at the Center and Surface of 0.96 Per cent Carbon Steel Cylinders Quenched from 875 Degrees Cent. (1605 Degrees Fahr.) into 5 Per Cent Sodium Hydroxide at Different Temperatures. Coolant Motion 3 Feet per Second; Cylinders ½ Inch Diameter by 2 Inches Long. Microstructures Originally × 500, Reduced 60 Per Cent in Printing. Samples Etched in 2 Per Cent Nitric Acid in Alcohol. Where Surface Structures Resembled those at the Center Only the Latter are Given.

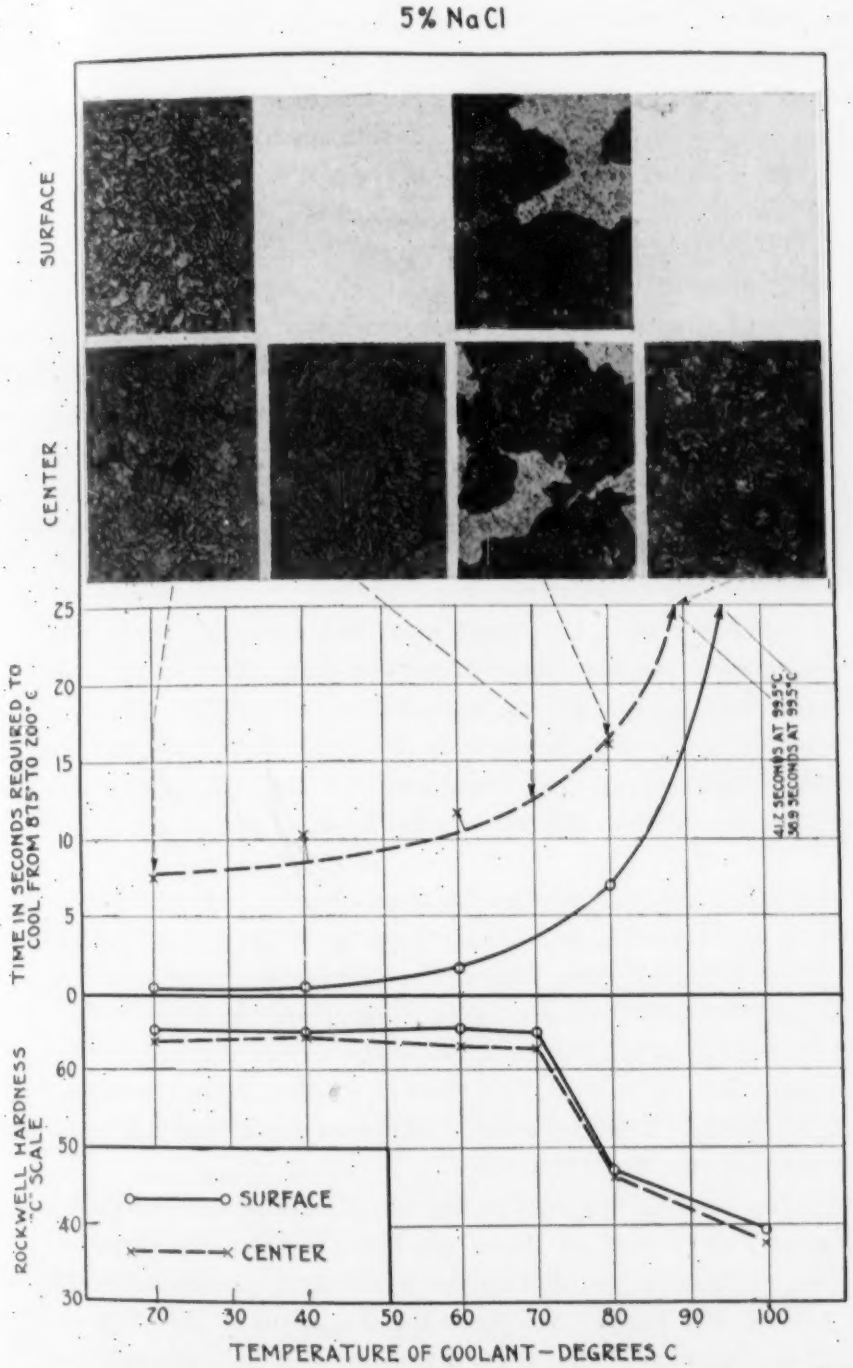

Fig. 6—Hardness, Cooling Times and Structure at the Center and Surface of 0.96 Per Cent Carbon Steel Cylinders Quenched from 875 Degrees Cent. (1605 Degrees Fahr.) into 5 Per Cent Sodium Chloride at Different Temperatures. Coolant Motion 3 Feet per Second; Cylinders ½ Inch Diameter by 2 Inches Long. Microstructures Originally × 500, Reduced 60 Per Cent in Printing. Samples Etched in 2 Per Cent Nitric Acid in Alcohol. Where Surface Structures Resembled those at the Center Only the Latter are Given.

a Rockwell "C" scale hardness of 63 to 65. This hardness was not attained at surface or center when the steel was quenched in either of the two oils, but was obtained at the center with water up to 60 degrees Cent., 5 per cent sodium chloride up to 70 degrees Cent. and 5 per cent sodium hydroxide up to 80 degrees Cent. (Fig. 10). With increase above the designated temperatures the hardness dropped appreciably and rapidly.

While water at 60 degrees Cent., 5 per cent sodium chloride at 70 degrees Cent. and 5 per cent sodium hydroxide at 80 degrees Cent. produced a Rockwell hardness equivalent to that obtained from the same coolants at atmospheric temperatures, there were appreciable differences in the structures of the quenched steels. In general, as the temperature of the coolant was increased, the structure changed from martensite (plus austenite) to martensite with increasing amounts of primary troostite and finally to troosto-sorbite and sorbite with some evidence of lamellar pearlite.

Emphasis should be placed upon the fact that the hardness of the martensitic samples practically free from troostite was substantially the same as that of the samples containing appreciable proportions of troostite. Hardness tests are frequently used in inspection to insure satisfactory heat treatment but may be inadequate when the properties desired are represented by martensite free from troostite.

Complete martensitization to the center of the ½ inch diameter cylinders was obtained only in the 5 per cent sodium hydroxide solution at 20 degrees Cent., whereas in previously reported tests[9] of a similar steel this was produced in water at 20 degrees Cent. This difference may be ascribed to differences in the critical cooling rates of the two lots of steel, i. e., different cooling rates are required by different heats of steel of similar carbon content for the production of martensite free from troostite.[10]

As has been indicated already the effects of temperature of the coolant on the cooling of the steels quenched in oils were small but opposite to the effects observed in water and the aqueous solutions. The cooling was slightly faster in the No. 2 oil at 100 degrees Cent. than at 20 degrees Cent. (Figs. 1 and 2) and this was confirmed by

[9]See foot note (1).

[10]General recognition of this is associated with the pioneer work on "abnormal" steels by McQuaid and Ehn, summarized along with more recent work in a paper by S. Epstein and H. S. Rawdon: "Steel for Case Hardening—Normal and Abnormal Steel." Bureau of Standards, *Journal of Research*, Vol. I, 1928, p. 423.

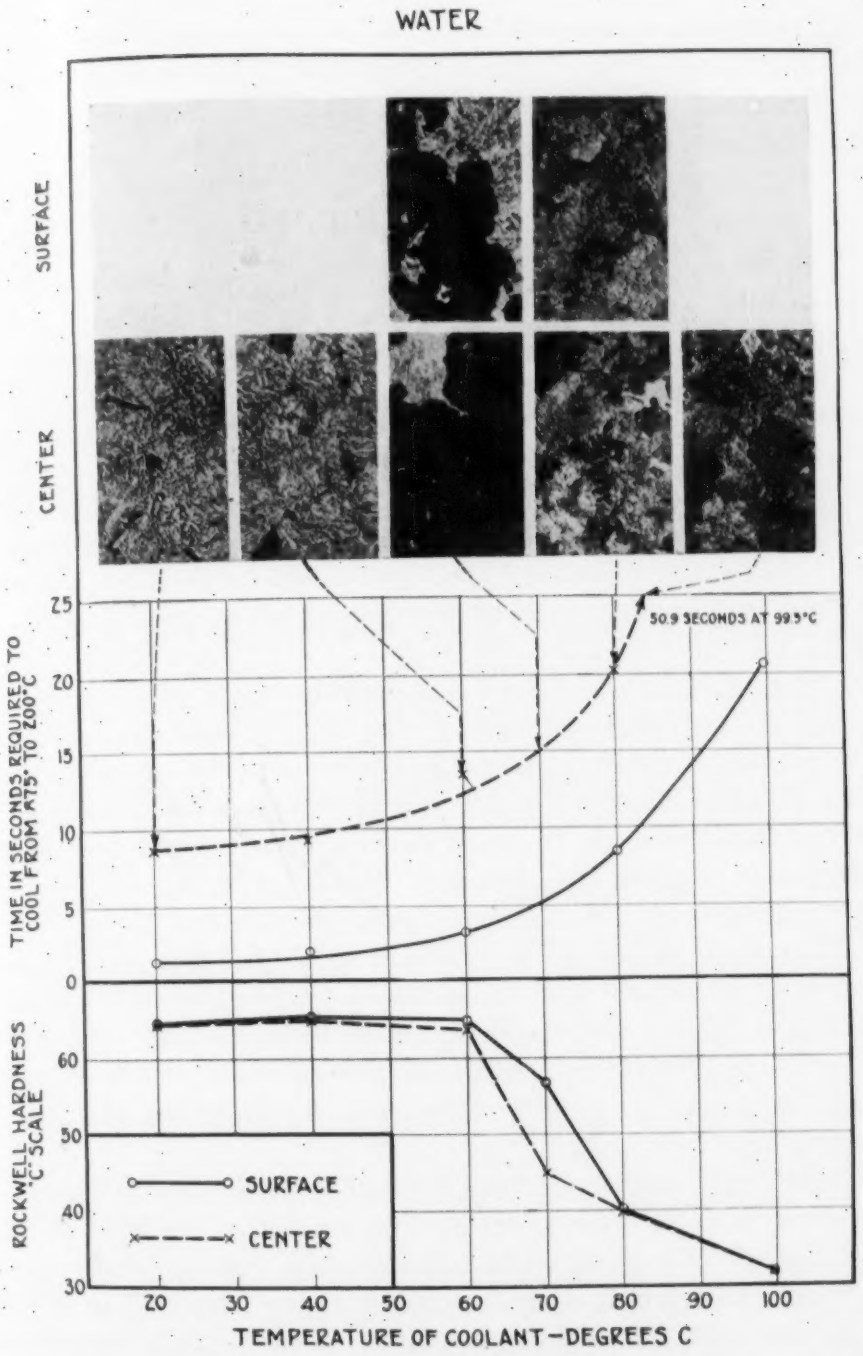

Fig. 7—Hardness, Cooling Times and Structure at the Center and Surface of 0.96 Per Cent Carbon Steel Cylinders Quenched from 875 Degrees Cent. (1605 Degrees Fahr.) into Water at Different Temperatures. Coolant Motion 3 Feet per Second; Cylinders ½ Inch Diameter by 2 Inches Long. Microstructures Originally × 500, Reduced 60 Per Cent in Printing. Samples Etched in 2 Per Cent Nitric Acid in Alcohol. Where Surface Structures Resembled those at the Center Only the Latter are Given.

the hardness tests reported in Fig. 8. A similar result was shown in the No. 1 oil (Fig. 9) but the changes were somewhat smaller. However, not all oils show increased speeds of cooling with increase in temperature[11] as in the two cases cited.

3. *Liquids with Graded Cooling Speeds*

Present day hardening practice is based quite largely upon the use of oils, water and the more rapid aqueous solutions such as sodium chloride brines, sodium hydroxide solutions, and water sprays at ordinary temperatures. There is a large gap between the cooling rates obtained in the customary quenching oils and in water, and this is now usually taken care of by tempering subsequent to hardening by or interrupted quenching. Such procedure is entirely satisfactory for many practical purposes, but simplification and economy and possibly also technical advantages would result if coolants were available to provide a more closely graded set of cooling characteristics.

The practical solution of this problem is not solely one of obtaining certain prescribed cooling rates since general availability and cost, permanence, safety from the standpoint of the operators, properties affecting adherence to the quenched metals which in turn affect the losses from the bath and cleaning costs, as well as other factors, should be given consideration. Nevertheless, one of the principal requirements is meeting certain prescribed cooling rates.

The liquids discussed in previous sections of this report offer a graded set of cooling rates from those of water and the more rapid aqueous solutions at atmospheric temperatures to those of the customary oils and in this respect they are of interest although only some would be classed as good or useful coolants from the viewpoint of practical heat treatment.

The most promising group, selected from the liquids considered are given in Table III in order of decrease in the speeds, or increase in the times, of cooling. The order given is correct insofar as the hardness, structures and center cooling times from 875 to 200 degrees Cent. (1605 to 390 degrees Fahr.) are concerned but not necessarily so for the cooling through other temperature ranges since the cooling curves of the different liquids do not all have the same form.

[11] J. A. Mathews and H. J. Stagg; "Factors in Hardening Tool Steel." *Transactions*, American Society of Mechanical Engineers, Vol. 36, 1914, p. 845.

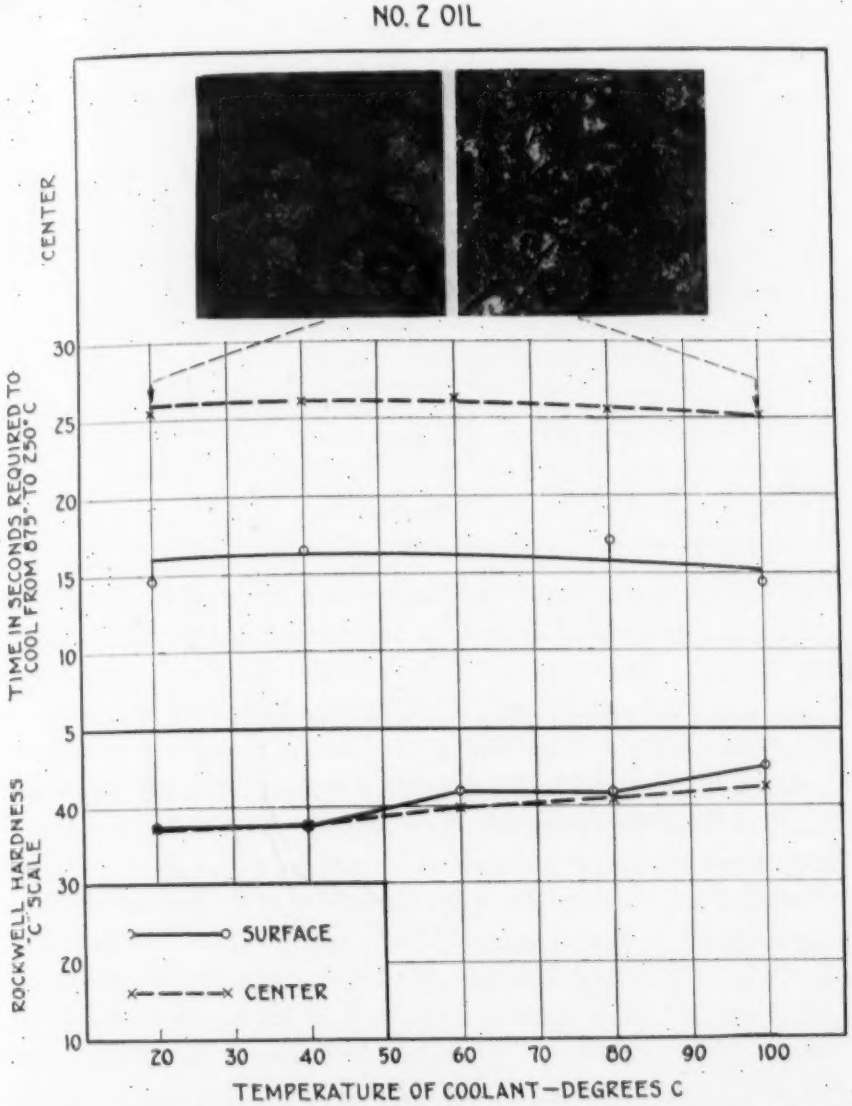

Fig. 8—Hardness, Cooling Times and Structure at the Center and Surface of 0.96 Per Cent. Carbon Steel Cylinders Quenched from 875 Degrees Cent. (1605 Degrees Fahr.) into No. 2 Oil at Different Temperatures. Coolant Motion 3 Feet per Second; Cylinders ½ Inch Diameter by 2 Inches Long. Microstructures Originally × 500, Reduced 60 Per Cent in Printing. Samples Etched in 2 Per Cent Nitric Acid in Alcohol. Where Surface Structures Resembled those at the Center Only the Latter are Given.

A list based on somewhat closer gradations can be prepared from the data in Figs. 1 to 10 inclusive, and substitutions can be made in a number of cases, but in Table III coolants showing the strongest tendencies toward irregular results have been omitted; only those were chosen in which smooth center cooling curves were obtained with fairly uniform slopes from 850 to 200 or 300 degrees Cent. (1560 to 390 or 570 degrees Fahr.).

Table III
List of Liquids Given in Order of Decrease in Cooling Speeds

Liquid and Temperature	Cooling time from 875° to 200°C (1) in seconds for Surface	Center
MORE RAPID THAN WATER		
5% NaOH at 20°C	0.31	7.8
5% NaCl at 20°C	0.48	7.4
WATER AT 20°C	1.2	8.6
RATES BETWEEN WATER AND OILS		
5% NaOH at 60°C	1.03	8.8
5% NaCl at 60°C	1.8	11.8
Water at 60°C	3.2	13.4
5% NaOH at 80°C	3.1	14.2
RATES CLOSE TO OR OF OILS		
5% NaOH at 85°C	{5.0}	{17.0}
5% NaOH at 90°C	{7.0}	{22.0}
No. 1 oil at 20°C	14.7	28.8
No. 2 oil at 20°C	19.3	29.7

(1) For 0.96 per cent carbon steel cylinders ½ inch diameter by 2 inches long; liquid moving at 3 ft. per second.
Bracketed values estimated by interpolation.

The corrosive nature of the hot sodium hydroxide solutions and the hot sodium chloride brines is at the same time an advantage and a disadvantage. These solutions would not be easy to handle industrially from the standpoint of either equipment or operators, but the quenched steels are relatively free from heavy scale, and with bath temperatures of 60 to 80 degrees Cent. or less, will often come out bright. This denotes active scale removal during the quench, an effect which tends to promote uniformity in the results obtained.

Observations during the experiments clearly indicated that as the temperature of the sodium chloride and hydroxide solutions approached the boiling point of water, there was a decided decrease in the uniformity of the conditions at the contact surfaces of the steel and the coolant. However, it should be kept in mind that all the experiments were made with low coolant velocities and that if better circulation were provided more uniform conditions could be expected. Liquids unsatisfactory at low rates of motion might become satisfactory at higher rates of motion.

4. Tensile Properties Produced by the Hot Aqueous Solutions

Two sets of tensile test bars were quenched in some of the hot aqueous solutions to give additional comparisons with water and the No. 2 oil at atmospheric temperatures. The first set was prepared from an oil hardening nickel-chromium steel while the second comprised specimens of 0.45 per cent carbon steel. The results of the tensile tests are summarized in Tables IV and V.

Table IV

Tensile Properties of a Cr-Ni Steel Quenched from 840 Degrees Cent. (1550 Degrees Fahr.) into Different Liquids Moving at 3 Feet Per Second[1]

(C 0.23, Cr 1.06, Ni 1.64, P 0.021, S 0.020)

Specimen No.	Coolant	Coolant Temp. °C.	Tensile Strength lbs./in.²	Breaking Strength[2] lbs./in.²	Elongation in 2 inches per cent	Reduction of Area per cent	Type of Fracture
5C-1	No. 2 oil	20	225,600	334,200	12.5	47.2	⅞ cup and cone—fibrous structure.
5C-2	No. 2 oil	22	225,000	321,400	12.0	44.1	⅝ cup and cone—fibrous structure.
Ave.			225,300	327,800	12.3	45.7	
5C-3	Water	70	246,000	308,000	9.0	33.1	⅞ cup and cone (deep elliptical)—fibrous structure.
5C-4	Water	71	232,400	358,000	12.0	49.0	Full cup and cone—fibrous structure.
Ave.			239,200	333,000	10.5	41.1	
5C-5	5% NaCl	80	232,800	294,500	9.5	26.2	½ cup and cone (deep elliptical)—fibrous.
5C-6	5% NaCl	81	230,900	278,000	9.0	25.1	½ cup and cone (deep)—fibrous structure.
Ave.			231,900	286,300	9.3	25.7	
5C-7	5% NaOH	80	236,000	369,000	13.0	51.1	⅝ cup and cone—fibrous structure.
5C-8	5% NaOH	80	235,500	361,500	13.0	50.0	⅝ cup and cone—fibrous structure.
Ave.			235,800	365,300	13.0	50.6	
5C-9	5% NaOH	85	232,500	313,000	10.0	34.7	½ thin cup and cone—fibrous structure.
5C-10	5% NaOH	85	230,800	301,000	9.5	30.2	⅝ thin cup and cone—fibrous structure.
Ave.			231,700	307,000	9.8	32.5	
5C-11	5% NaOH	90	200,700	245,000	7.5	20.0	Sharp, rather flat break—fibrous structure.
5C-12	5% NaOH	90	198,800	243,500	6.5	20.0	Sharp, flat break—fibrous structure.
Ave.			199,800	244,300	7.0	20.0	

[1]Specimens were held 30 minutes at temperature before quenching.
[2]The load at fracture divided by the area of the fractured section.

Table V

Tensile Properties of a 0.44 Per Cent Carbon Steel Quenched from 815 Degrees Cent. (1500 Degrees Fahr.) Into Different Liquids Moving at 3 Feet Per Second[1]

(C 0.44, Mn 0.81, P 0.025, S 0.022)

Specimen No.	Coolant	Coolant Temp. °C.	Tensile Strength lbs./in.[2]	Breaking Strength[2] lbs./in.[2]	Elongation in 2 inches per cent	Reduction of Area per cent	Type of Fracture
7A-1	No. 2 oil	18	128,500	135,200	1.5	4.7	Fine crystalline structure—sharp break.
7A-2	No. 2 oil	21	148,500	158,000	1.0	5.9	Fine crystalline structure—sharp break.
Ave.			138,500	146,600	1.3	5.3	
7A-3	Water	70	106,500	111,500	3.0	4.5	Fine crystalline structure—sharp break.[3]
7A-4	Water	70	127,200	198,800	14.0	54.8	⅞ deep cup and cone—fibrous structure.
Ave.			116,900	155,200	8.5	29.7	
7A-5	5% NaCl	79	119,200	189,300	17.0	47.2	⅝ deep cup and cone—fibrous structure.
7A-6	5% NaCl	81	118,500	201,000	17.5	51.7	⅝ deep cup and cone—fibrous structure.
Ave.			118,900	195,200	17.3	49.5	
7A-7	5% NaOH	80	Both specimens cracked in quenching.				Very fine crystalline structure—sharp break.
7A-8	5% NaOH	80					Very fine crystalline structure—rather sharp break.
7A-9	5% NaOH	85	77,500	80,800	1.0	4.0	Very fine crystalline structure—sharp break.
7A-10	5% NaOH	85	95,700	98,700	1.0	2.8	Very fine crystalline structure—rather sharp break.
Ave.			86,600	89,800	1.0	3.4	
7A-11	5% NaOH	90	114,700	200,000	20.5	55.3	¾ cup and cone—fibrous structure.
7A-12	5% NaOH	90	114,700	195,600	20.5	54.2	⅝ cup and cone—fibrous structure.
Ave			114,700	197,800	20.5	54.8	

[1]Specimens were held 30 minutes at temperature before quenching.

[2]The load at fracture divided by the area of the fractured section.

[3]Instability as referred to in text.

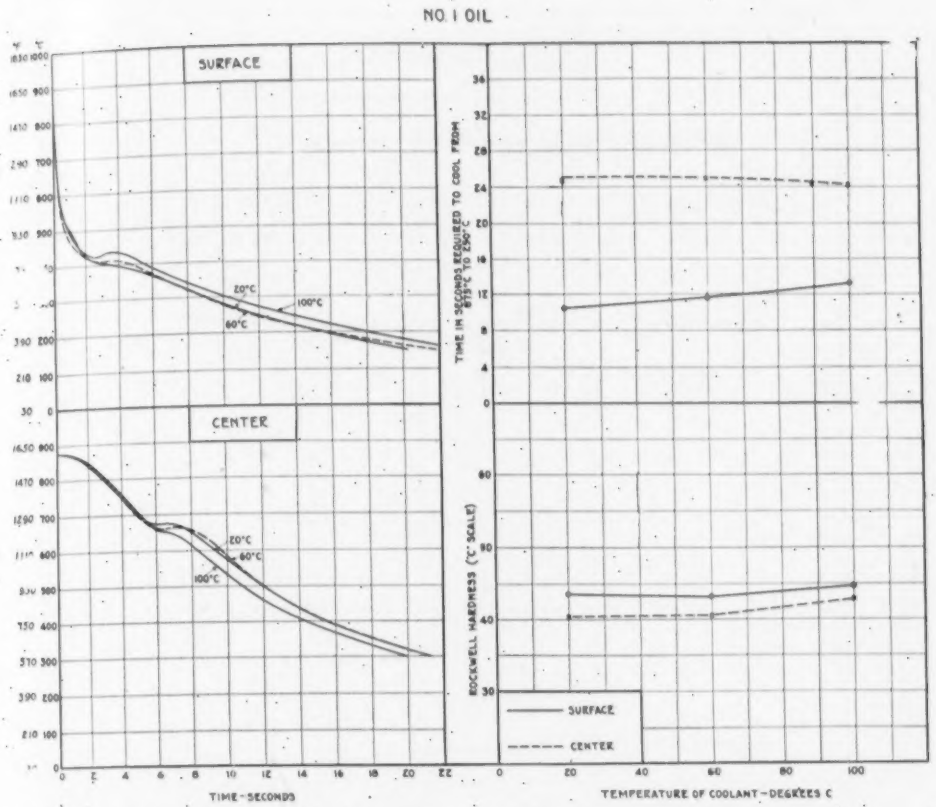

Fig. 9—Cooling Curves, Cooling Times and Hardness at Center and Surface of 0.96 Per Cent Carbon Steel Cylinders Quenched in No. 1 Oil at Different Temperatures. Coolant Motion 3 Feet per Second; Cylinders ½ Inch Diameter by 2 Inches Long.

In the case of the nickel-chromium steel (Table IV) somewhat better uniformity was obtained in the two oil-quenched samples than in those which were quenched in water at 70 degrees Cent. but the best combination of strength and ductility was obtained in samples quenched in 5 per cent sodium hydroxide at 80 degrees Cent. The results obtained with 5 per cent sodium chloride at 80 degrees Cent. were not as good as those with the sodium hydroxide at 80 degrees Cent. but as the temperature of the sodium hydroxide was increased to 85 and 90 degrees Cent. there was a decrease in both the strength and ductility.

The specimens of 0.45 per cent carbon steel cracked when quenched in the 5 per cent sodium hydroxide at 80 degrees Cent. (Table V). Poor mechanical properties were obtained in the same liquid at 85 degrees Cent. but when the temperature was raised to 90 degrees Cent. an excellent combination of strength and ductility was obtained. Good strength, elongation and reduction of area were

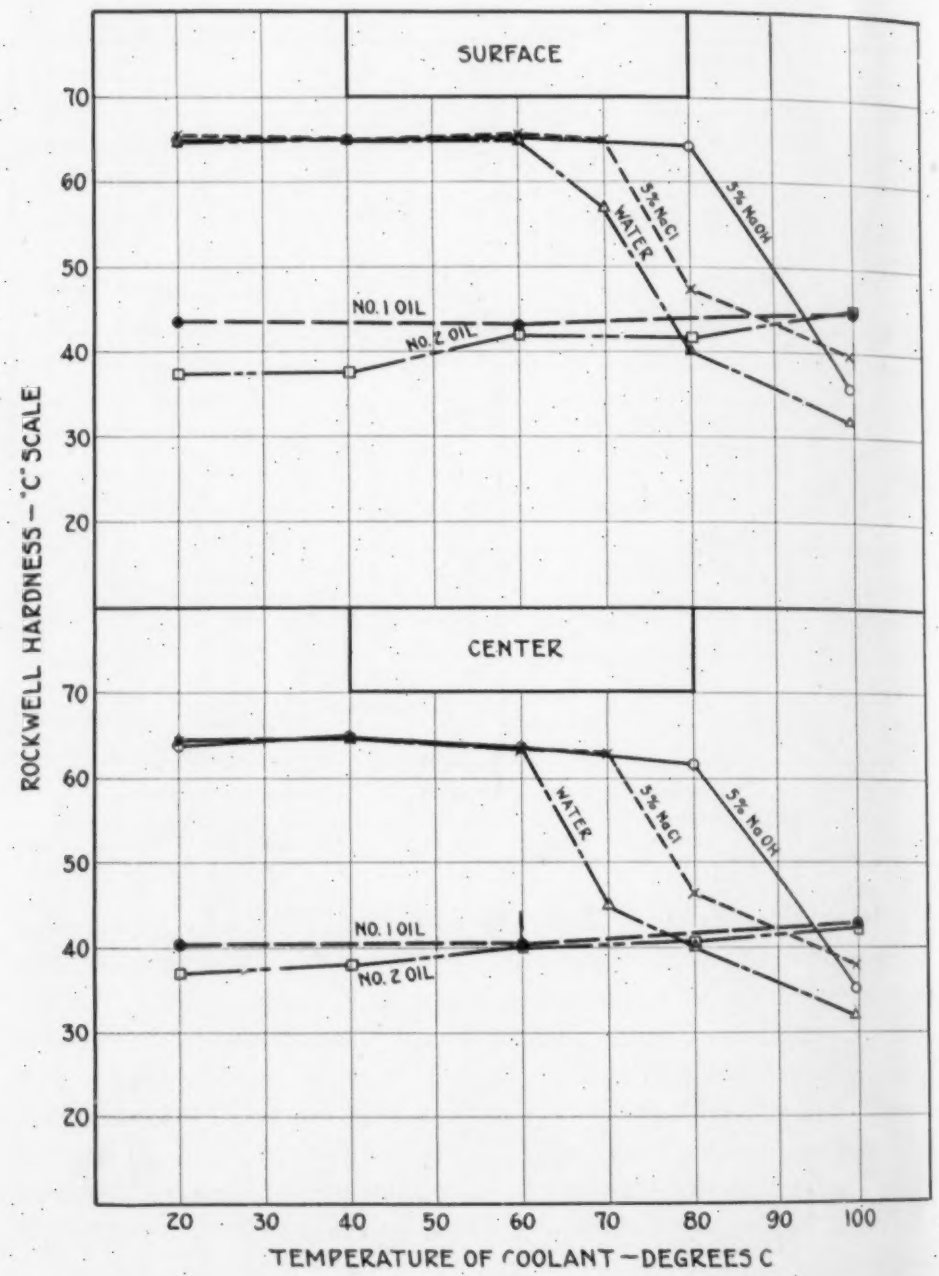

Fig. 10—Surface and Center Hardnesses of the 0.96 Per Cent Carbon Steel Cylinders Quenched from 875 Degrees Cent. (1605 Degrees Fahr.) into Different Liquids at different Temperatures. Coolant Motion 3 Feet per Second; Cylinders ½ Inch Diameter by 2 Inches Long.

also obtained in 5 per cent sodium chloride at 80 degrees Cent. but erratic results were obtained in water at 70 degrees Cent. Hankins

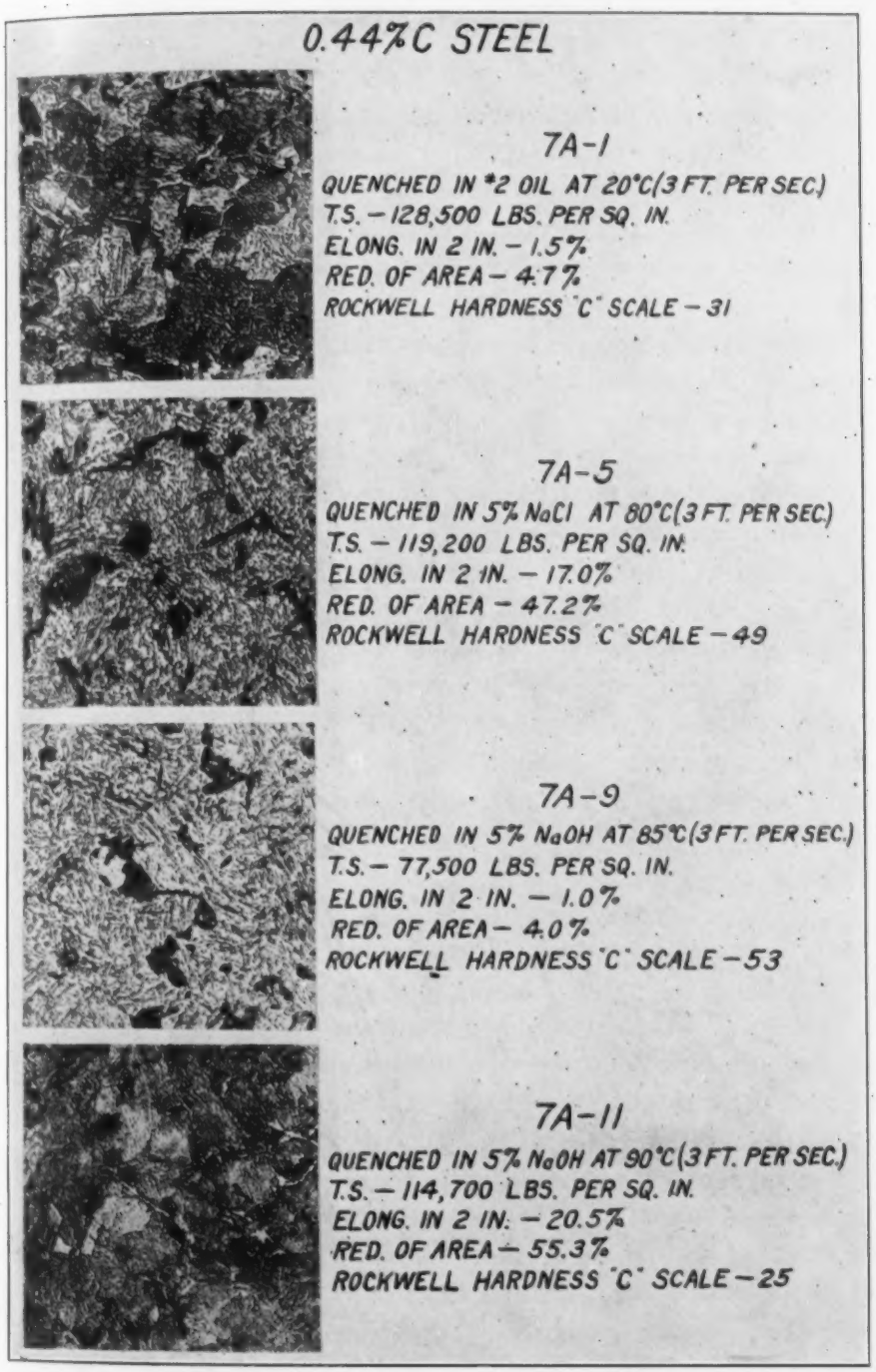
0.44%C STEEL
7A-1
QUENCHED IN #2 OIL AT 20°C(3 FT. PER SEC.)
T.S. – 128,500 LBS. PER SQ. IN.
ELONG. IN 2 IN. – 1.5%
RED. OF AREA – 4.7%
ROCKWELL HARDNESS 'C' SCALE – 31
7A-5
QUENCHED IN 5% NaCl AT 80°C(3 FT. PER SEC.)
T.S. – 119,200 LBS. PER SQ. IN.
ELONG. IN 2 IN. – 17.0%
RED. OF AREA – 47.2%
ROCKWELL HARDNESS 'C' SCALE – 49
7A-9
QUENCHED IN 5% NaOH AT 85°C(3 FT. PER SEC.)
T.S. – 77,500 LBS. PER SQ. IN.
ELONG. IN 2 IN. – 1.0%
RED. OF AREA – 4.0%
ROCKWELL HARDNESS 'C' SCALE – 53
7A-11
QUENCHED IN 5% NaOH AT 90°C(3 FT. PER SEC.)
T.S. – 114,700 LBS. PER SQ. IN.
ELONG. IN 2 IN. – 20.5%
RED. OF AREA – 55.3%
ROCKWELL HARDNESS 'C' SCALE – 25

Fig. 11—Microstructures and Physical Properties of Some of the Tensile Specimens Tested, Summarized in Table V. Microstructures which were Taken at Center of the Tensile Specimens Originally × 500, Reduced 46 Per Cent in Printing. Samples Etched in 2 Per Cent Nitric Acid in Alcohol.

and Ford[12] tried unsuccessfully to quench 18-inch tensile specimens, 3 inches wide and ⅜ inch thick of a 0.60 per cent carbon steel from 800 degrees Cent. (1470 degrees Fahr.) into water at 50 degrees Cent. without cracking after being successful with 3 and 6-inch plates of the same width and thickness.

The structures of some of the tensile test specimens are shown in Figs. 11 and 12. The No. 2 oil at 20 degrees Cent. and the 5 per cent sodium hydroxide at 90 degrees Cent. produced a troosto-sorbitic structure in the 0.45 per cent carbon steel while the 5 per cent sodium chloride at 80 degrees Cent. and the 5 per cent sodium hydroxide at 85 degrees Cent. produced a martensitic structure containing appreciable proportions of troostite. The differences in ductility and tensile strength in samples 7A-9 and 7A-5, Fig. 11, were probably due in part to differences in the degree of tempering of the martensite, to differences in the proportions of troostite present and to differences in the residual stresses left by the volume changes in hardening.

The three nickel-chromium steel samples shown in Fig. 12 showed structures consisting of partially tempered martensite; in the sample quenched in 5 per cent sodium hydroxide at 90 degrees Cent. dark needles were found suggesting the presence of troostite. These samples showed low tensile strength and ductility in comparison with the samples quenched in oil at 20 degrees Cent. or 5 per cent sodium hydroxide at 80 degrees Cent.

5. *Dimensional Changes in the Hot Aqueous Solutions*

Gages of the form and dimensions shown in Fig. 13 were quenched in each of the two oils and in some of the hot aqueous solutions and the resulting changes in diameter and in the width of the slot A are summarized in Table VI.

The gages used were similar to those employed in the inspection of class 5 tool steels by the U. S. Navy Department[13] except that they were exactly half size in all dimensions. Johanssen gage blocks were used in measuring the width of the slot A while the diameters were measured at points ¼ inch to ½ inch from each side of the slot A.

[12] G. A. Hankins and G. W. Ford; "The Mechanical and Metallurgical Properties of Spring Steels as Revealed by Laboratory Tests." A paper presented before the 1929 spring meeting of the British Iron and Steel Institute.

[13] 0.80 to 1.05 per cent Carbon, 1.25 to 2.00 per cent Manganese; Navy Department Specifications for Tool Steel, No. 47S5c, July 1, 1921.

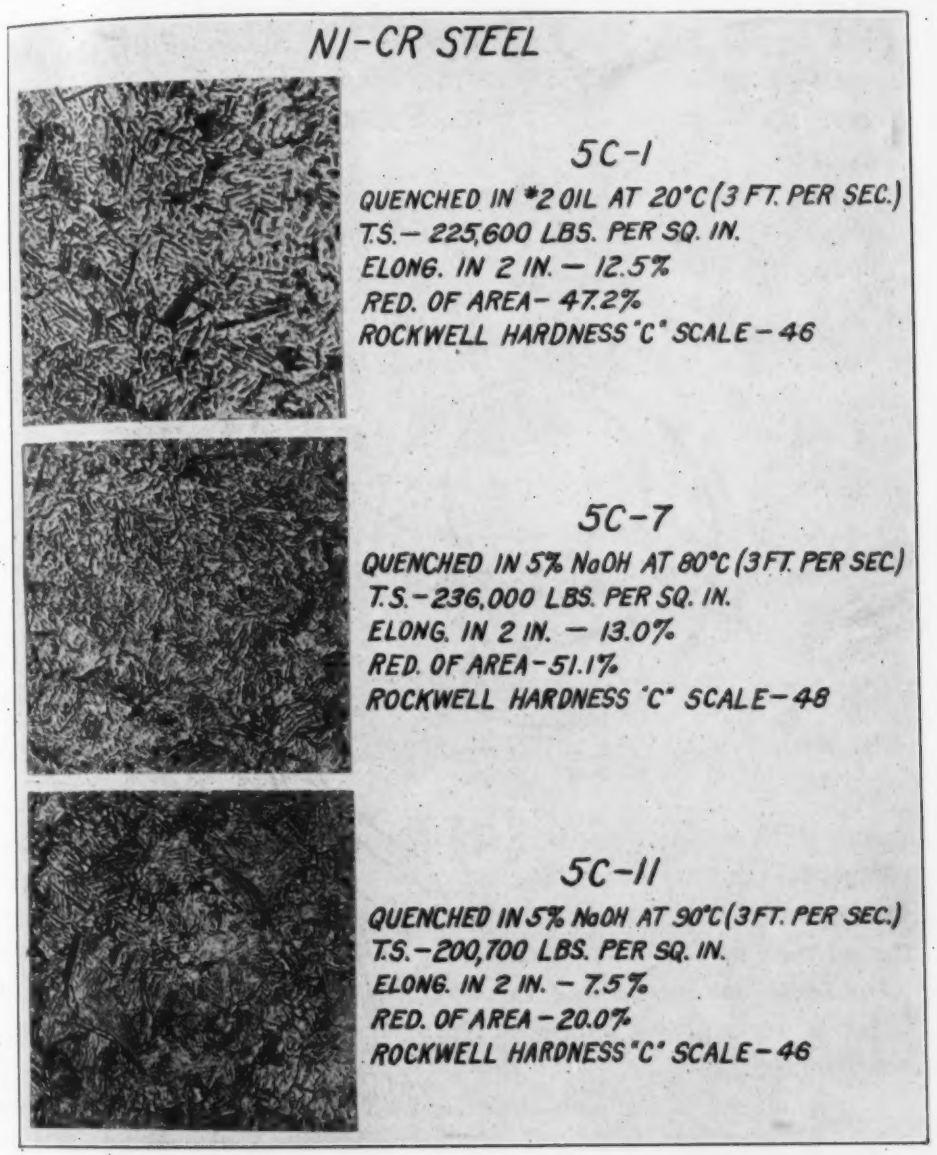
NI-CR STEEL
5C-1
QUENCHED IN #2 OIL AT 20°C (3 FT. PER SEC.)
T.S.– 225,600 LBS. PER SQ. IN.
ELONG. IN 2 IN. – 12.5%
RED. OF AREA – 47.2%
ROCKWELL HARDNESS "C" SCALE – 46
5C-7
QUENCHED IN 5% NaOH AT 80°C (3 FT. PER SEC.)
T.S. – 236,000 LBS. PER SQ. IN.
ELONG. IN 2 IN. – 13.0%
RED. OF AREA – 51.1%
ROCKWELL HARDNESS "C" SCALE – 48
5C-11
QUENCHED IN 5% NaOH AT 90°C (3 FT. PER SEC.)
T.S. – 200,700 LBS. PER SQ. IN.
ELONG. IN 2 IN. – 7.5%
RED. OF AREA – 20.0%
ROCKWELL HARDNESS "C" SCALE – 46

Fig. 12—Microstructures and Physical Properties of Some of the Tensile Specimens Tested, Summarized in Table IV. Microstructures which were Taken at Center of the Tensile Specimens Originally × 500, Reduced 40 Per Cent in Printing. Samples Etched in 2 Per Cent Nitric Acid in Alcohol.

The gages were all brought to a constant temperature of 20 degrees Cent. before measurements were made.

For the first quench the gages were placed in a furnace at 815 degrees Cent. (1500 degrees Fahr.) held 45 minutes and immersed in the chosen liquid. After the desired measurements had been

made, the gages were tempered for one hour at 230 degrees Cent. (445 degrees Fahr.) and again measured. Subsequently, the gages were repeatedly quenched into the solutions first used but in these cases they were held in the furnace only 15 minutes before quenching.

The steel originally selected for the tests was an "oil hardening" steel containing about 0.9 per cent carbon, 1.2 per cent manganese and about 0.5 per cent each of chromium and tungsten but due to an

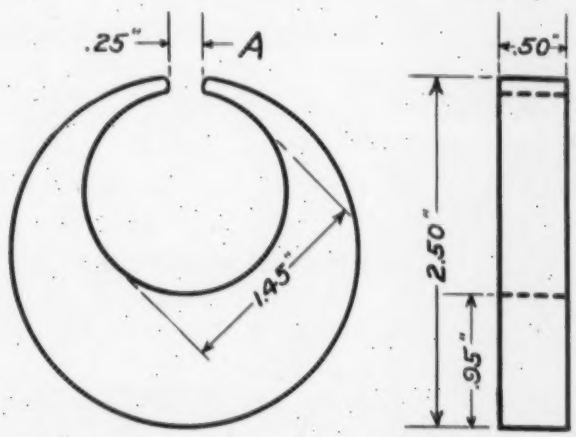

Fig. 13—Form and Dimensions of the Gage Used in the Repeated Quenching Experiments.

error which was not discovered until after the experiments had been completed the gages were made from a steel containing 0.45 per cent carbon and 1 per cent chromium. However, this latter steel served the purpose of the experiments since the coolants of greatest interest were those having cooling rates between the oils and ordinary tap water at atmospheric temperatures and an "oil hardening" steel was not essential.

The object of the tests described was to detect in a practical and empirical manner conditions which might be characterized as dangerous in the application of the different coolants. The form of the specimen illustrated in Fig. 13, with its thin and heavy sections, precludes uniform cooling and the stresses set up by the volume changes in hardening cannot readily be calculated on account of the complexity of the conditions encountered in different parts of the gage, but should certainly be high. Therefore, this specimen offers a means of detecting strong tendencies of the different coolants to promote distortion and cracking, irrespective of the causes of these effects.

The changes in diameter may be taken to indicate roughly the

Table VI

Dimensional Changes and Cracking of the Gages Shown in Fig. 13 when Repeatedly Cooled in Different Liquids

Coolant (moving at 3 ft./sec.)	Dimension A, Fig. 13 in annealed steel, inch	Change in A, Fig. 13, upon quenching from 815°C individual specimens, inch	Change in A, Fig. 13, upon quenching from 815°C average inch	Further change in A, Fig. 13, upon tempering at 230°C individual specimens, inch	Further change in A, Fig. 13, upon tempering at 230°C average inch	Diameter change on quenching from 815°C individual specimens, inch	Diameter change on quenching from 815°C average inch	Rockwell Hardness ("C" Scale) after 1st quench	Rockwell Hardness ("C" Scale) after 1st quench and tempering at 230°C	Repeated Quenching from 815°C into specified coolant
No. 2 oil at 20°C	0.2482	+ 0.0037	+ 0.0029	+ 0.0004	+ 0.0004	+ 0.0037	+ 0.0032	51	50	
	0.2482	+ 0.0021		+ 0.0003		+ 0.0027		52	50	
No. 1 oil at 20°C	0.2484	− 0.0001	+ 0.0005	+ 0.0005	+ 0.0006	+ 0.0025	+ 0.0026	52	49	
	0.2483	+ 0.0010		+ 0.0007		+ 0.0027		51	49	
Water at 70°C	0.2483	+ 0.0090	+ 0.0108	+ 0.0006	+ 0.0005	+ 0.0072	+ 0.0072	57	52	Cracked on 5th quench
	0.2485	+ 0.0125		+ 0.0004		+ 0.0072		57	51	Cracked on 5th quench
5% NaCl at 80°C	0.2485	+ 0.0134	+ 0.0144	+ 0.0008	+ 0.0008	+ 0.0056	+ 0.0056	57	51	Not cracked on 9th quench
	0.2482	+ 0.0153		+ 0.0007		+ 0.0056		55	52	Not cracked on 9th quench
5% NaOH at 80°C	0.2477	+ 0.0026	+ 0.0026	+ 0.0001	+ 0.0001	+ 0.0028	+ 0.0028	55	51	Cracked on 3rd quench
	0.2483	cracked						56	51	Cracked on 1st quench
5% NaOH at 90°C	0.2484	+ 0.0076	+ 0.0080	+ 0.0005	+ 0.0005	+ 0.0017	+ 0.0019	57	50	Not cracked on 9th quench
	0.2485	+ 0.0084		+ 0.0005		+ 0.0021		55	51	Not cracked on 9th quench

815 degrees Cent. or 1500 degrees Fahr.
230 degrees Cent. or 445 degrees Fahr.

volume changes in hardening while those in the width of the slot A, Fig. 13, should reflect qualitatively the magnitude of the internal stresses set up by these volume changes since the ends forming the slot are free to move.

As is shown in Table VI the changes in the width of the slot A, Fig. 13, were larger, per unit of measured length, than those in the diameter of the gages but the two sets of changes showed simultaneous increases or decreases when comparing the different coolants. With one exception, the changes were larger in the hot aqueous solutions than in the oils (Table VI). This one exception was the sodium hydroxide at 80 degrees Cent. in which the dimensional changes were about equal to those in the No. 2 oil and smaller than the changes in any of the other liquids except the No. 1 oil. The Rockwell hardness produced in metal adjacent to the slot was somewhat higher when the gages were quenched in the sodium hydroxide at 80 degrees Cent. (55, "C" scale) than when quenched in either of the oils (51 or 52 for both oils).

In all cases the changes produced by tempering for one hour at 230 degrees Cent. (445 degrees Fahr.) were small, and this may be taken to indicate that the widening of the slot in quenching effectively relieved a large part of the internal stresses produced by the volume changes in hardening.

The results obtained in these experiments justify the view that some of the hot aqueous solutions can be useful in bridging the gap between the cooling rates obtained with water and oils at ordinary temperatures, but some of their characteristics must be recognized as sources of danger or disadvantage. The maintenance of rapid cooling at low temperatures may be undesirable in the hardening of some steels but this also applies to drastic coolants such as the cold brines and cold sodium hydroxide solutions now used industrially. Difficulties from this source can be minimized in some cases, at least, by removing the steel before it reaches coolant temperatures (interrupted quenching) and under suitably controlled conditions any benefits derived need not be at the expense of high hardness. Another source of danger in the hot aqueous solutions is lack of uniformity, promoted by the formation of relatively large amounts of steam but this becomes more marked as the bath temperature approaches the boiling point of water and can probably be counteracted through adequate circulation and adjustment of coolant composition and temperature.

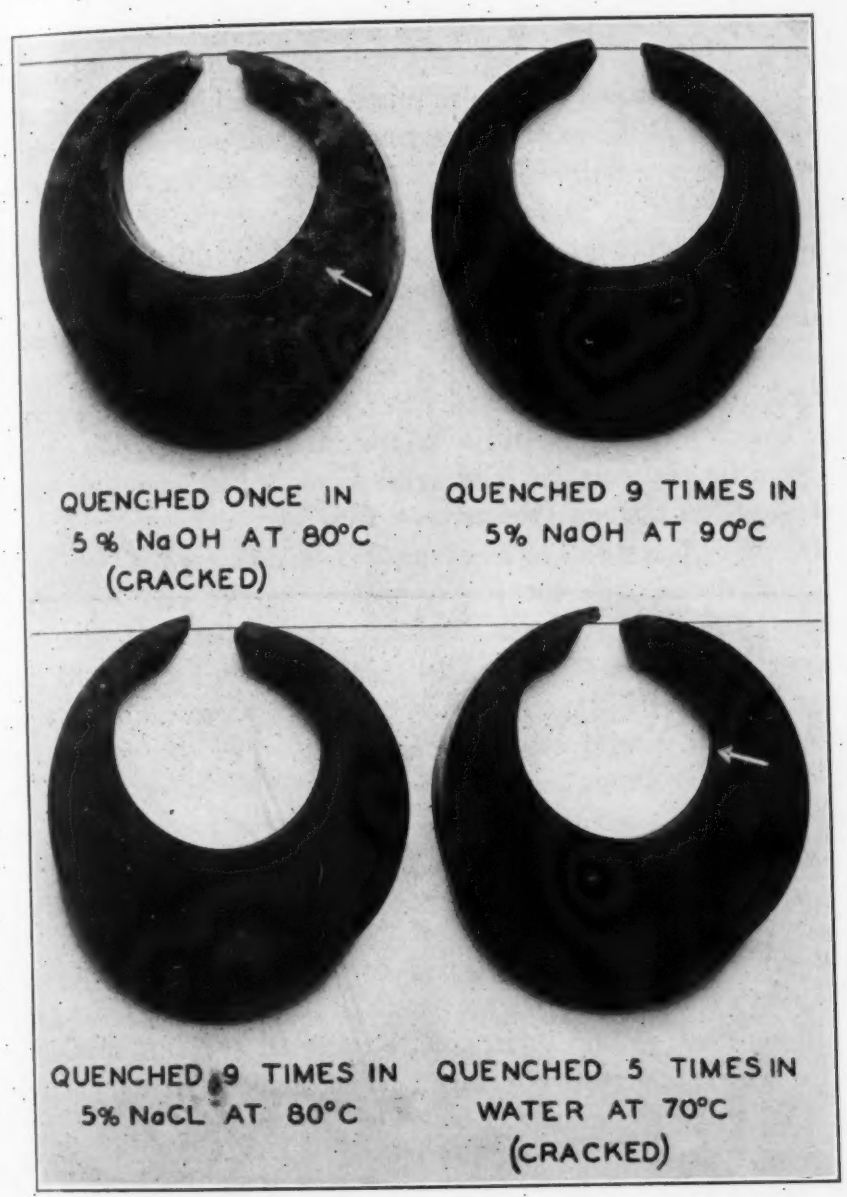

Fig. 14—Some of the Gages after Repeated Quenching in Some of the Hot Aqueous Solutions. Arrows Point to Cracks.

Such sources of danger are well recognized but the hot aqueous solutions studied are not necessarily "poisonous" to steels as is illustrated by the results of the repeated quenching summarized in Table VI.

Under the adverse conditions imposed by repeated introduction of the hardened steels into a furnace at high temperatures, without

intermediate annealing, two of the gages cracked in the first and third quenchings in the 5 per cent sodium hydroxide at 80 degrees Cent. but five treatments were required for cracking in water at 70 degrees Cent. and the gages did not crack when quenched nine times in either 5 per cent sodium chloride at 80 degrees Cent. or 5 per cent sodium hydroxide at 90 degrees Cent.

The appearance of some of the repeatedly quenched gages is shown in Fig. 14, and it will be observed that considerable distortion has taken place in the ends forming the slot in those gages which were quenched nine times without cracking. The cracks in the gages quenched in 5 per cent sodium hydroxide at 80 degrees Cent. were in the heavy section (see arrows, Fig. 14), whereas those in the gages quenched in water at 70 degrees Cent. were circumferential at the hole in the specimen (see arrows, Fig. 14).

Not enough tests have been made to determine the best of the liquids tested for different purposes nor the order of uniformity which may be expected under conditions of practical application but the described results seem to justify the conclusion that the hot aqueous solutions will, upon further study of concentrations and circulation, offer a useful set of coolants to bridge the gap between water and oils at atmospheric temperatures, at least for the hardening of small steel parts.

IV. Summary

1. Surface and center cooling curves were obtained on cylinders of 0.96 per cent carbon steel, ½ inch in diameter and 2 inches long, when quenched from 875 degrees Cent. (1605 degrees Fahr.) into water, 5 per cent sodium hydroxide, 5 per cent sodium chloride solutions and two proprietary quenching oils at different temperatures between 20 and 100 degrees Cent. The liquids were all moving at 3 feet per second and the cooling curves were correlated with the microstructures and the hardnesses produced in the cylinders.

2. Increase in temperature lowered the cooling speeds, and increased the cooling times in water and the aqueous solutions but the changes were smaller between 20 and 60 degrees Cent. than between 60 and 100 degrees Cent. Exactly opposite effects were produced in the center cooling by the two oils but the changes were relatively small throughout the entire temperature range, 20 to 100 degrees Cent.

3. As the temperature of the aqueous solutions approached the

boiling point of water, the cooling at the surfaces of the cylinders became more irregular and the cooling rates at low temperatures around 200 or 300 degrees Cent. (390 or 570 degrees Fahr.) became more rapid than at intermediate temperatures around 300 to 500 degrees Cent. (570 to 930 degrees Fahr.) or at higher temperatures. However, smooth center cooling curves were obtained in water at temperatures up to and including 60 degrees Cent. or the 5 per cent solutions of sodium hydroxide or sodium chloride up to 80 degrees Cent.

4. These characteristics suggested the possibility of using the hot aqueous solutions to bridge the gap in cooling rates between water and the customary quenching oils at ordinary temperatures. The following were selected as the most promising of the liquids tested and are given in order of decrease in average cooling speeds (increase in center cooling times) over the range, 875 to 200 degrees Cent. (1605 to 390 degrees Fahr.) 5 per cent NaOH at 20 degrees Cent.; 5 per cent NaCl at 20 degrees Cent.; water at 20 degrees Cent.; 5 per cent NaOH at 60 degrees Cent.; 5 per cent NaCl at 60 degrees Cent.; water at 60 degrees Cent.; 5 per cent NaOH at 80 degrees Cent.; 5 per cent NaOH at 85 or 90 degrees Cent; the two proprietary oils at 20 to 100 degrees Cent.

5. Not all of these would be classed as good coolants for practical heat treatment and substitutions or additions can be made from the group studied but experimental application of some of the hot aqueous solutions in the quenching of medium carbon steel and nickel-chromium steel tensile test bars and a limited study of the dimensional changes and cracking of carbon-chromium steel gages of special form showed promising possibilities. The results seem to justify the view that the hot aqueous solutions should, with further study of concentrations and circulation, ultimately provide a useful set of coolants having speeds intermediate between water and oils at atmospheric temperatures, at least in the hardening of small pieces of steel.

Acknowledgements

Acknowledgement is made to H. K. Herschman, associate metallurgist, for the photomicrographs, to H. A. Bright, associate chemist, for the chemical analysis of the steels, and to H. T. Kennedy and T. S. Sly of the oil section, for the test data on the two quenching oils.

DISCUSSION

Written Discussion: By F. R. Palmer, Carpenter Steel Co., Reading, Pennsylvania.

I have read this interesting paper with the same pleasure that I did the earlier ones by Messrs. French and Klopsch. Each time the Bureau publishes a paper on this subject, I feel that they should be complimented and encouraged to continue their work on this interesting and difficult subject. The present paper is valuable because it reduces to understandable figures things which have existed in the minds of steel treaters in a very intangible and hazy form.

I feel that the authors should step lightly in suggesting the possibility of substituting a properly regulated quenching speed for a full quench followed by a suitable temper. Quenching—at best—is subject to variables which are, at the present time, beyond the hardener's control. These variables are caused by the size and the shape of the piece being quenched so that different parts and different areas must of necessity receive different quenching effects. Such being the case, strains are bound to be present and anticipated structures will fail to materialize in certain unfavorable areas. In the present state of the art, it would seem much safer to subject the piece to a quenching speed sufficiently rapid to form a uniformly hardened structure—even in the most inaccessible areas—and then temper the parts to secure the proper combination of hardness and toughness.

It would also seem that the temperature of the quenching bath, for purposes described in this paper, is more sensitive than the furnace temperatures where the steels are heated. That is, a difference of 10 degrees in the heating temperature probably would not greatly affect the parts being hardened, whereas the authors point out that this small variation makes quite a difference in the quenching effects of both brine and sodium hydroxide around 80 degrees Cent., which appears to be their most interesting temperature. For commercial service, this would require accurate thermostatic control involving both heating and refrigerating facilities in the quenching bath.

I note that martensite forms at the center of the specimens with lower cooling speeds than is required to form martensite at the surface. Do the authors have any explanation for this effect?

It is sincerely hoped that the authors will continue their efforts to reduce the quenching operation to understandable figures and we look forward hopefully to obtaining further data from them along this line.

Since my discussion was written, an interesting example has been presented which further emphasizes the last paragraph.

Some two years ago, a problem was presented in the form of a coining die which was subjected to a pressure of 200,000 pounds per square inch. The die was irregular in shape and while there are a number of tool steels which should theoretically be able to withstand this pressure successfully, the complete list of die steels had been exhausted without yielding a production in excess of 3,000 to 5,000 pieces

per die. Apparently this enormous stress was in excess of the fatigue limit of the die and the section would break after a relatively short run.

The subject was studied from a standpoint of quenching strains—the idea being to design a flushing fixture which would set up internal strains favorable to the purpose instead of strains which weakened the die. The quenching apparatus design was rather complicated and required several changes before it was finally approved. I believe the apparatus cost in the neighborhood of $30. This figure is mentioned to show that quenching fixtures are not something to be lightly disposed of with a few pieces of pipe and a couple of fittings—or a length of rubber hose.

Using the same design of die, and the same tool steel, these same dies are now producing 50,000 pieces per die—all of which can be credited to quenching. Therefore, any work that the Bureau turns out which will reduce quenching to a mathematical science, so that somebody can sit down and figure out how to make these quenching strains work for industry instead of against industry, is certainly very much worth while.

Written Discussion: By John L. Cox, Midvale Co., Nicetown, Philadelphia.

The paper by Messrs. French and Hamill is a very interesting continuation of the quantitative studies on quenching media by Messrs. French and Klopsch, which have appeared from time to time.

The question of the permissible temperature range of a quenching medium is one of much practical importance, to which the authors have made a distinct contribution.

There was no reason to doubt the superior cooling effect of a 5 per cent solution of sodium hydroxide over water at ordinary temperatures, and it might be thought a corollary that it would retain a satisfactory cooling rate at higher temperatures than would water. However, presumption is not proof, and this the authors have now given.

The delayed cooling rate in oil occurring at about 450 degrees Cent. is doubtless due to the liberation of heat as the steel passes the Ar_1 point, masked for very rapid cooling rates but observable when the raised temperature of coolants ordinarily more rapid reduces their cooling rate to one approximating that of cold oil. Had the authors' specimens been of decidedly larger size we believe the same phenomenon would have been evident at lower temperatures of coolant.

It is interesting to have an actual measurement of the difference in cooling time between water at 20 and at 40 degrees Cent. That there was a decided difference in the effects was well known to those having to harden sensitive steels. That a difference in cooling time of approximately 60 per cent should have made no difference in the surface hardness of the authors' samples, under conditions precluding the production of austenite, is surprising.

For more than twenty years it has been the practice of the Midvale Company and its predecessors to quench in warm water such steels as chrome-vanadium when it was desired to secure higher physical prop-

erties than could be produced by oil quenching, and an unmachined surface made cold water quenching hazardous because of the liability to longitudinal cracking. To secure uniformity of surface hardness it was found necessary to limit the water temperature to a maximum of about 55 degrees Cent. with a preferred temperature of about 45 degrees Cent. The authors' curves, showing a great increase in quenching time to occur with water between 40 and 60 degrees Cent. confirm practical experience.

We fully concur in the conclusions of the paper that water at temperatures above normal can be used for rates of cooling intermediate between water at its usual temperature and oil. A wider range of permissible temperature is evidently available with aqueous solutions if one is willing to incur the inconveniences their use entails.

It is to be regretted that the authors used such small specimens that for most purposes their quantitative measurements are practically qualitative only. Also, it is very confusing to have three different scales used in one diagram, although we recognize the limitations of space.

Author's Closure

Probably the only question requiring further discussion is the one raised by F. R. Palmer regarding the retention of martensite at the center of steel samples when cooled at rates below those at which martensite was found at the surface.

There are at least two reasons to account for this state of affairs. The first has to do with the form of the cooling curves obtained at center and surface. While the cooling velocities at around 700 degrees Cent. may be the same, the subsequent cooling at lower temperatures may be much slower at the surface than at the center and result in a lower order of hardening, perhaps troostite or sorbite, instead of martensite. Illustrations of these effects are found in the charts included in the paper. As Mr. Palmer has himself so aptly stated the situation the initial cooling velocities provide the "will to harden" but whether hardening is accomplished is also dependent upon the subsequent cooling.

A second and, possibly, the most important, variation is in the stress conditions within the metal. In the early stages of cooling the outside (surface) tends to contract on the inside (center). The center is in compression which, in all probability, tends to delay the austenite-martensite transformation by opposing its normal volume increase. It is conceivable, under such conditions, that martensite might result at the center and under comparable cooling rates at high temperatures a lower order of hardening be produced at the surface.

These are merely suggestive lines of thought since the conditions encountered in the practical hardening of steels are ordinarily complex and a complete explanation is difficult, if not impracticable, at this time.

THE BRITTLE RANGE IN 18 AND 8 CHROMIUM-NICKEL IRON

By H. H. Lester

Abstract

Chromium-nickel iron with less than 0.1 per cent carbon, with 8 per cent nickel and 18 per cent chromium is austenitic at room temperature. It becomes relatively brittle on heating to about 1300 degrees Fahr. (705 degrees Cent.) In the specimens studied a well defined critical point was found at 1330 degrees Fahr. (720 degrees Cent.) on heating and at 1148 degrees Fahr. (620 degrees Cent.) on cooling. It is suggested that this critical point is associated with the loss of ductility.

The loss of ductility is regarded as being due to the formation of ferrite crystals and to the precipitation of iron or chromium carbide along atomic planes in austenite grains that normally would be favorable to slip.

The precipitation seems to be a consequence of plastic deformation of the metal. At the temperature of maximum brittleness and with a relatively small amount of mechanical work the ferrite crystals and carbide particles tend to remain diffused within the austenite grains which are rendered brittle thereby. With relatively greater amounts of mechanical working the carbides tend to collect along grain boundaries forming uncoagulated aggregations of submicroscopic particles. At more elevated temperatures the carbides tend to collect at grain boundaries but in coagulated masses.

THE fact that chromium-nickel iron of about 18 per cent chromium and 8 per cent nickel develops brittleness on heating to about 1300 degrees Fahr. (705 degrees Cent.) is well known and is of considerable importance in various high temperature services where this metal is used. The Ordnance Department of the U. S. Army has investigated this material for possible application in ordnance construction. The results of the tests seem to indicate the

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A paper presented before the Eleventh Annual Convention of the society, Cleveland, September 9 to 13, 1929. The author, H. H. Lester, a member of the society, is research physicist, Watertown Arsenal, Watertown, Mass. Manuscript received April 18, 1929.

cause of such brittleness and are considered of sufficient value to industry to warrant publication.

The material used was tested as received without additional thermal treatment over that given by the manufacturer. Its chemical composition was as follows:

Carbon	Manganese	Silicon	Sulphur	Phosphorus	Nickel	Chromium
0.095	0.35	0.370	0.012	0.010	8.84	18.20

The present investigation included a critical point determination, a series of tensile tests, and microscopical examination.

The critical point determination was made by H. C. Knowlton under the direction of Captain S. B. Ritchie in charge of heat treating.

The tensile tests were made at room temperature at 200 degrees Fahr. and thence at intervals of 200 degrees Fahr. up to and including 2000 degrees Fahr. One specimen was tested at 1180 degrees Fahr. and the next in the series at 1400 degrees Fahr. After rupture the specimens were removed from the furnace and allowed to cool in air. The specimens were standard 0.505-inch tensile test bars, two inches between gage marks. The tensile data were secured by H. C. Mann, in charge of physical tests, who supplied also curves of Figs. 1 and 2.

Results Obtained

Tensile results are shown graphically in Fig. 1. It may be seen that minimum reduction and elongation occur at 1400 degrees Fahr. It is considered probable that these minima would have occurred close to 1330 degrees Fahr. had additional tests been made between 1180 and 1400 degrees Fahr.

Fig. 2 shows the critical points on heating and cooling. They are well defined.

Thermal curves taken on material of similar composition but containing about 2 per cent silicon showed only a slight thermal arrest at these points and curves taken on material of similar composition except that it contained 2 per cent silicon and 3.7 per cent tungsten showed no critical points at all. Both of these materials, however, showed typical loss of ductility at temperatures around 1400 degrees Fahr. (760 degrees Cent.).

Metallographic Tests

The broken specimen tested at 1400 degrees Fahr. (760 degrees Cent.) and one tested at 1800 degrees Fahr. (982 degrees Cent.) were selected for microscopic examination. These were marked N7 and N11 respectively. Sections from each of these were taken parallel to the axis of the bar at the ruptured end and in the enlarged

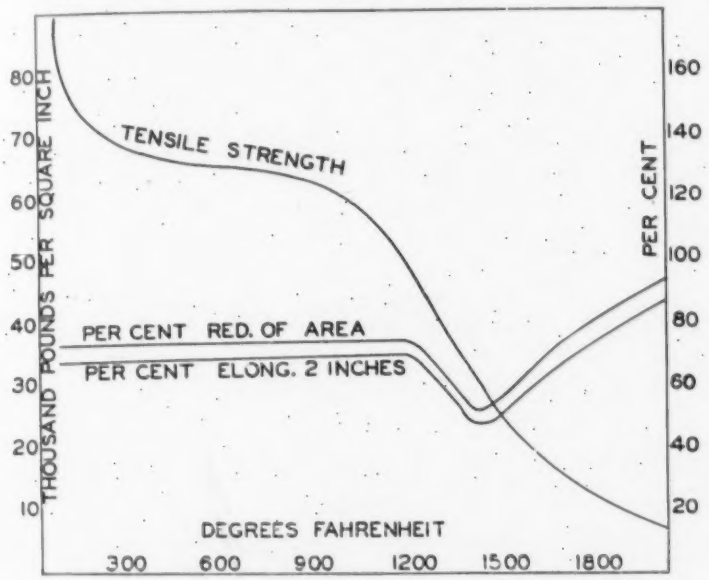


Fig. 1—Curve Showing Tensile Properties at Various Temperatures as Shown by Short Time Tests. The Minimum Ductility was Found at 1400 degrees Fahr., but no Specimens were Pulled Between 1180 degrees Fahr. and 1400 degrees Fahr. The Change in Ductility Does Not Seem to Affect the Tensile Strength Curve.

threaded ends of the standard 0.505-inch tensile test specimens. The sections were marked N7A, N7B, N11A and N11B. The "A" sections were from the ruptured ends, the "B" sections from the threaded ends of the bars.

Figs. 3 and 4 show typical grain boundary conditions in the mid portion of N7B. This was the brittle specimen. Near the edge of the section and close to the base of the threads of the specimen slip planes were abundant. The grain boundaries were for the most part fairly sharp with no indication of segregated constituents.

Fig. 5. shows typical boundary conditions near the ruptured end. The indefinite boundaries became more frequent as the rupture was approached. Figs. 6 and 7 were obtained just behind the rupture. In fact a partial rupture between grains is shown in one part of the

picture. In Fig. 7 there can be no question but that some constituent has been precipitated and part of it has traveled to the vicinity of the grain boundaries. Figs. 6 and 7 will repay considerable study. In other cases, as shown later, the carbides did not etch and appeared in the microscope as brilliant masses standing in relief. Here they etch black. This is thought to indicate that in this case the carbide is very finely divided and is in fact almost amorphous. Each black speck is regarded as made up of an agglomeration of still finer ones,

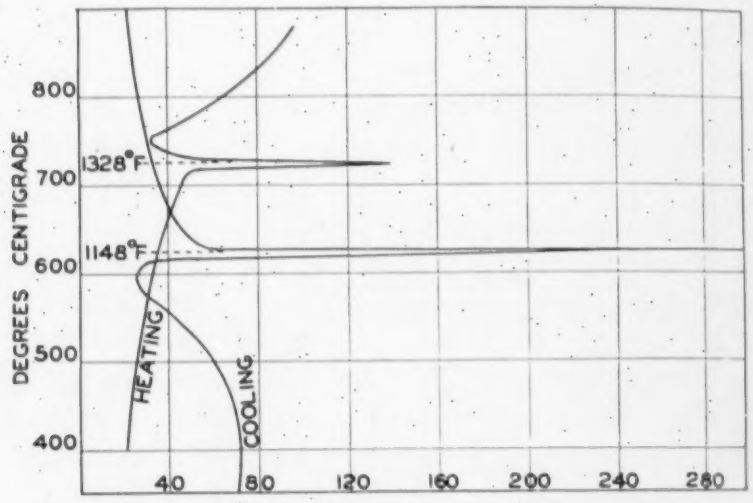


Fig. 2—Thermal-Critical Curves of Steels, Composition:—carbon 0.095 per cent, manganese 0.35 per cent, silicon 0.37 per cent, sulphur 0.012 per cent, phosphorus 0.010 per cent, nickel 8.84 per cent, chromium 18.20 per cent.

and represents a very early stage in coalesence. This black material originates within the grain. In Fig. 6 it has not in all places entirely reached the grain boundary. Where in the grain did it come from? Evidently the carbide was first precipitated along atomic planes that normally would have been favorable to slip. Under applied stress relative movements among atoms seem to facilitate the migration of the carbide masses towards regions of lower stress intensity.

Fig. 7 shows the most striking example found of the migrating carbides. Many grains were practically free of the effect and showed clean boundaries. At first this fact was taken to indicate a relative inequality in carbon content, but later it was observed that while many intergranular ruptures were observed in this region, in all cases observed such ruptures were along the clean boundaries, and in no case was rupture found along boundaries similar to those of the

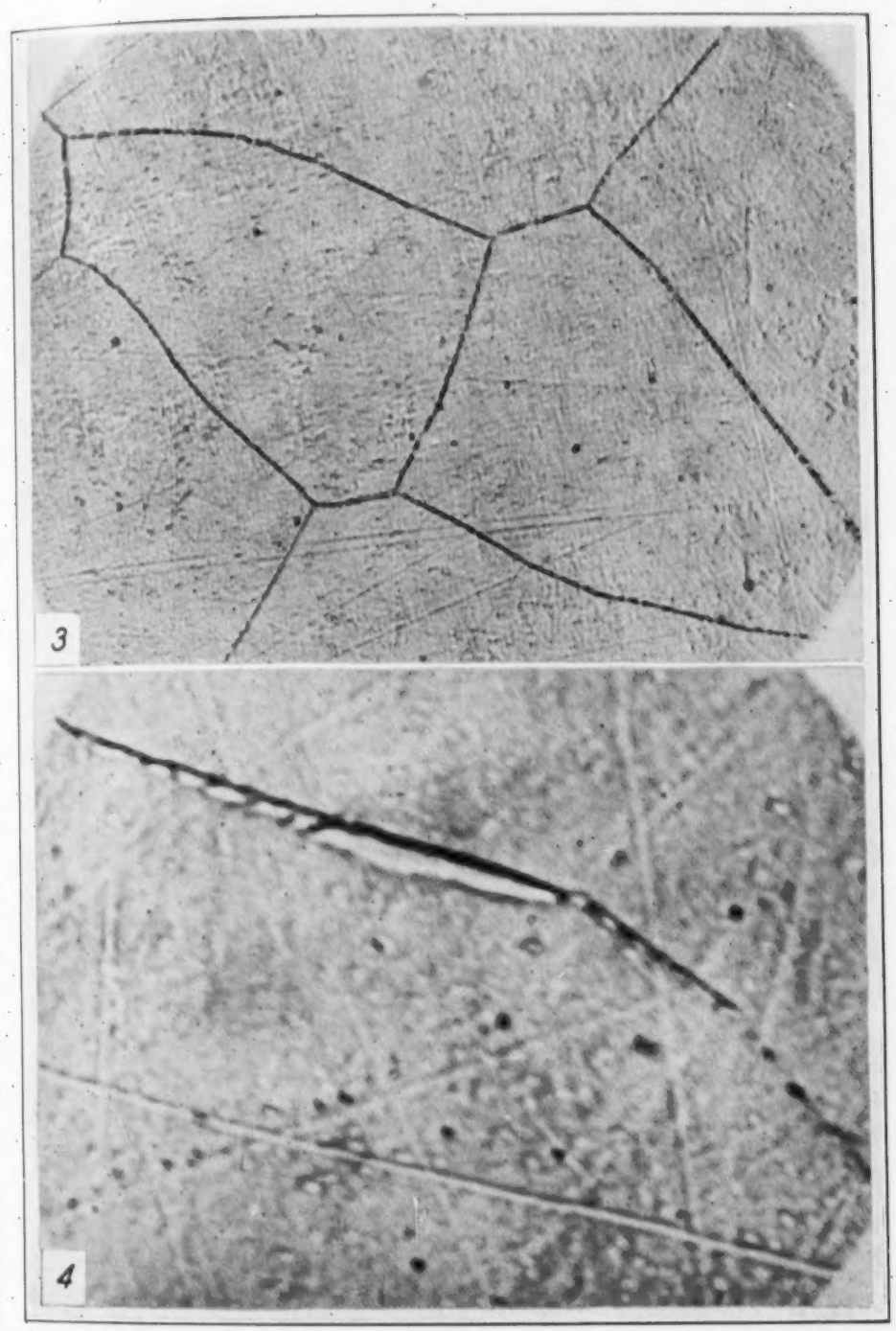


Fig. 3—Photomicrograph Showing Typical Grain Boundaries in the Center of the Test Bar at the End Remote from the Rupture. × 1000.

Fig. 4—Photomicrograph Showing Chipped Edges Found Along Some Grain Boundaries. In this Case the Broken Fragments were Still in Place. This Chipping was no Doubt Done in Polishing but it Attests the Brittleness of the Material Within the Grain. × 3000.

complete grain of Fig. 7. Could it be that these grains for some reason have not rejected the interfering carbides and that these particles are still preventing slip and so making the grain relatively rigid? No other explanation seems to fit the facts as well. Incidently it may be remarked that these pictures seem to give concrete evidence in favor of the brilliant concept of slip interference offered by Dr. Jeffries as the explanation of and the definition of plastic hardness.

Figs. 8 and 9 show typical boundary conditions in the "B" section of N11, the more ductile specimen. Slip planes were frequent all through this region. In general the grain boundaries were clear. They tended to etch into broad lines and in a few cases some segregations were found. Spots appeared within the grains. These did not etch and stood in relief. It is thought that these represent ferrite masses. In the "A" section, however, the case was different as illustrated in Figs. 10 to 13.

Fig. 10 shows a grain boundary that appears to be a row of cavities. It is regarded that inclusions have been removed from these cavities. This was taken after a relatively light etch. Considerable difficulty in polishing this section was encountered, but before etching the surface appeared to be free from polishing marks. After the light etch polishing marks seem to predominate. Fig. 11 shows the effect obtained somewhat closer to the rupture and after more prolonged etching. Note that the polishing scratches seem to have disappeared. Here the inclusions are predominantly at grain boundaries and are isolated masses. In some cases groups of these inclusions were found away from grain boundaries as shown in Fig. 13. Figs. 12 and 13 show very clearly the fact that the cloudy masses of Fig. 6 are here coagulated. The particles in these figures were quite brilliant as viewed in the microscope. They polished in relief, indicating that they are harder than the adjacent metal.

The above study seems to point to the fact that carbides are precipitated and that these tend to travel to grain boundaries under the influence of strain in the metal. They coagulate into larger masses at elevated temperatures. Some grains show little if any of this effect, others show it quite pronounced. This may indicate a lack of uniform distribution of carbon.

The case for the cause of brittleness does not depend entirely on grain boundary conditions. As observed above there were differences in the slip planes in the two cases. Figs. 14 and 15 are from

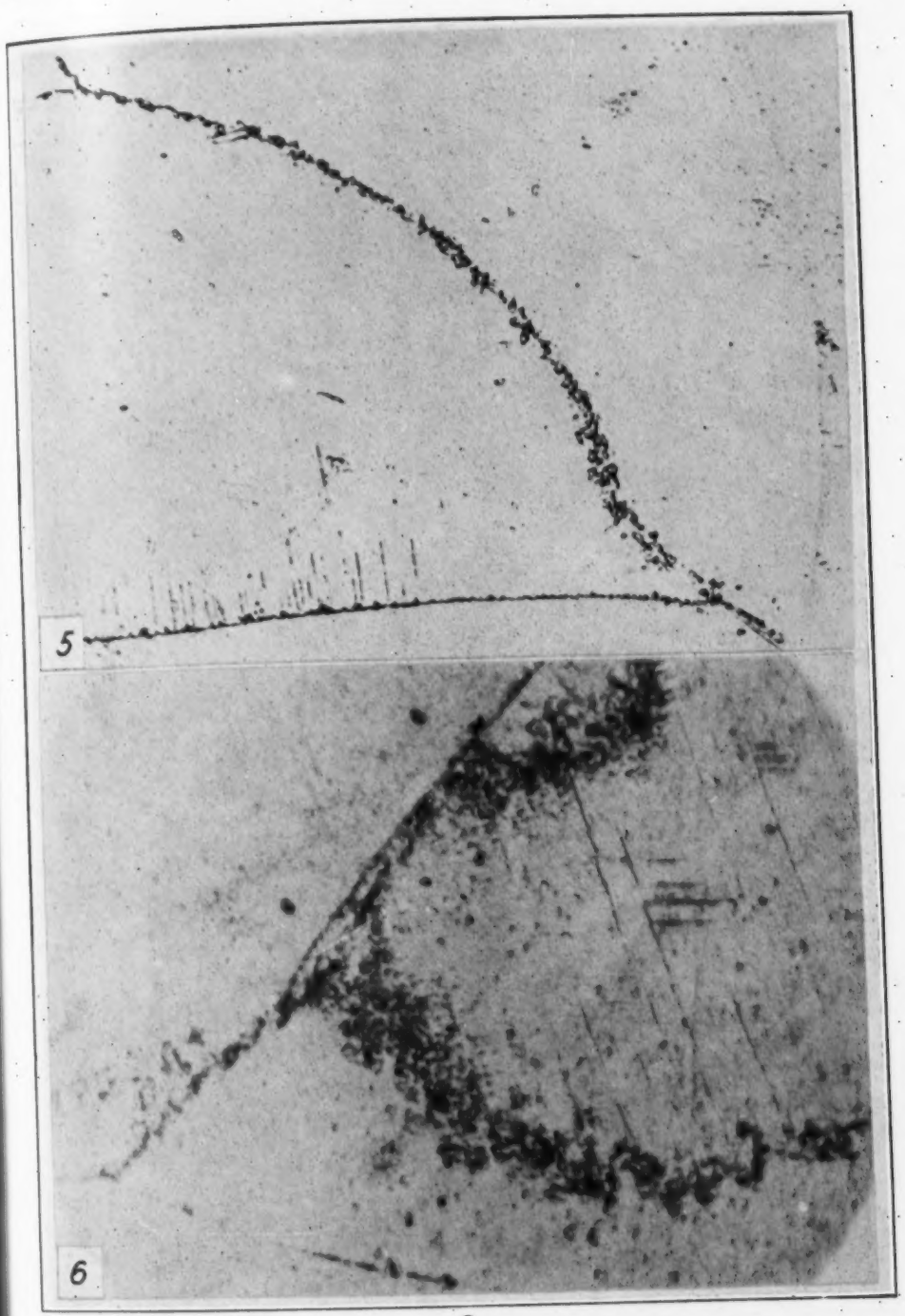


Fig. 5—Typical Photomicrograph of Many Grain Boundaries Near the Ruptured End of N7. In This Picture at Least Part of the Irregularities Found are Due to Broken Material at the Boundary. × 1000

Fig. 6—Photomicrograph Showing Segregations Within Grain Tending to Collect at Grain Boundaries. × 3350.

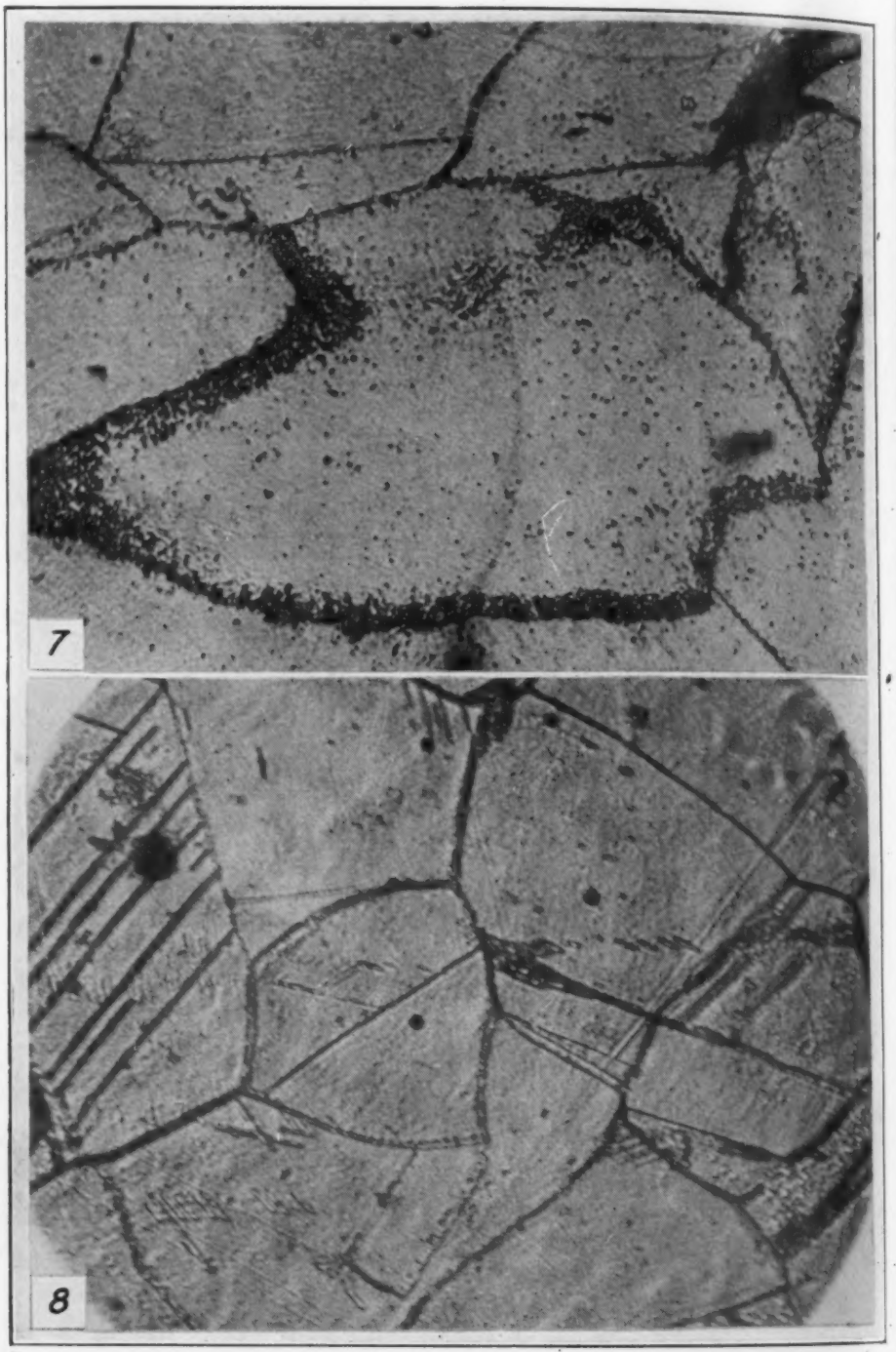


Fig. 7—Photomicrograph Taken Just Behind the Rupture. In the Complete Grain there is an Obvious Concentration of Some Constituent at the Grain Boundaries and Fine Particles may be Seen Throughout the Grain. In no Case were the Ruptures Along Boundaries Similar to those of the Full Grain in the Above Picture but they were Always Along Clean Boundaries. Each of the Black Particles in the Above Picture is Regarded as Representing an Agglomeration of Submicroscopic Carbide Particles. This Picture Catches them in an Early Stage of Coalesence. × 1000.

Fig. 8—Photomicrograph Showing Grain Boundaries in the B Section. In Some Cases the Broadened Boundaries Represent Differences in Level Between Adjacent Grains. × 500.

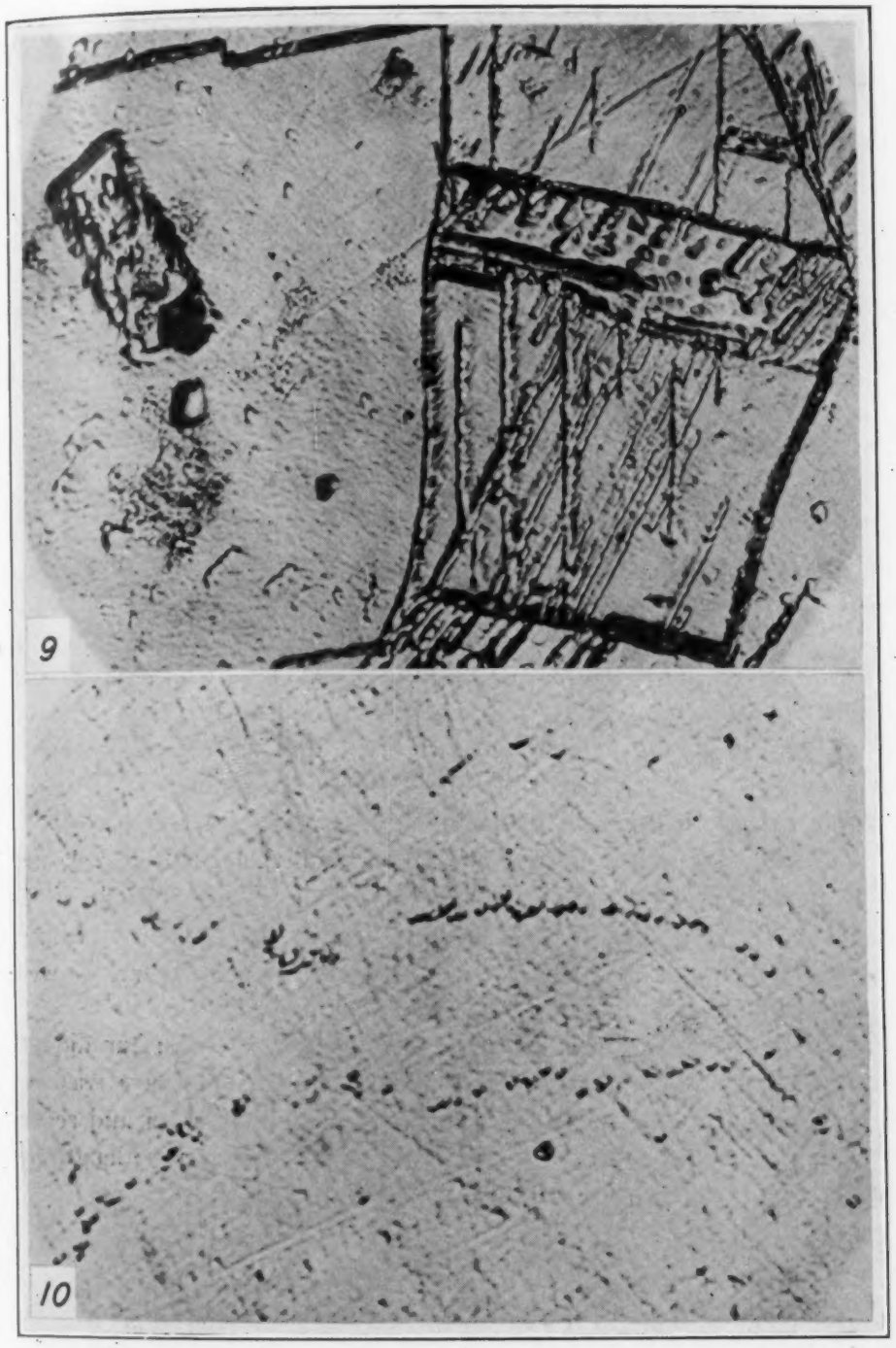


Fig. 9—Spot Near Center of Grain Toward Left Probably Represents Ferrite Segregation, Found Mostly in N77 Specimen.

Fig. 10—Photomicrograph Taken After Relatively Light Etch. Showing Grain Boundary in A Section of Ductile Specimen. Probably Carbides Have Fallen Out of the Cavities Shown. × 1500.

the "B" section of N7 and at a point near the base of the threads where slip planes were found abundantly. Fig. 16 is somewhat more remote from the threads.

Figs. 17 and 18 are from a point in the "A" section of N7. These show irregularities in the slip planes that suggest that while slip planes are found they are not formed with entire ease. Very few slip planes were found at all in the region of N7B remote from the threads. The irregularities in slip planes that occur are similar except on a smaller scale to those noted by Grossmann.[1] He ascribed the irregularities to resistance to slip caused by precipitated carbides. He assumed irregular distribution of carbon. His carbide particles were probably larger than those of the N7 specimen.

In Fig. 19 are shown typical slip plane conditions in N11B near the base of the threads where the slip planes in both specimens were most marked. Note the greater quantity of them and a greater regularity. Fig. 20 shows similar conditions toward the ruptured end of the bar, but well back from the rupture. There is obviously greater ease of formation and greater regularity in the slip planes in the more ductile specimen. That is, this evidence indicates greater relative rigidity in the grains of N7 than of N11. Such greater rigidity must be associated with greater resistance to slip which suggests that carbides might have been precipitated along atomic planes that would normally have been favorable to slip.

In the case of the more ductile specimen the tensile bar showed typical necking down at the rupture. The grains just back of the rupture were peculiar in that they showed no evidence of twinned crystals and no slip planes. In fact the only details observable were the grain boundaries even after prolonged etching.

In the case of the less ductile specimen the tensile bar did not neck down, although even at the minimum ductility there was still a reduction of area of about 50 per cent. The elongation and reduction of area appeared to be uniform throughout the entire length between gage marks, even at the point of rupture.

Discussion of Results

The experimental evidence presented above seems to point to the fact that the loss of ductility noted may be ascribed rather to a stif-

[1] M. A. Grossmann, "Behavior of Carbon in High Carbon Rustless Iron," Transactions, American Society for Steel Treating, Vol. X, September, 1926, in a study of 18 per cent chromium, 0.08 per cent carbon steel.

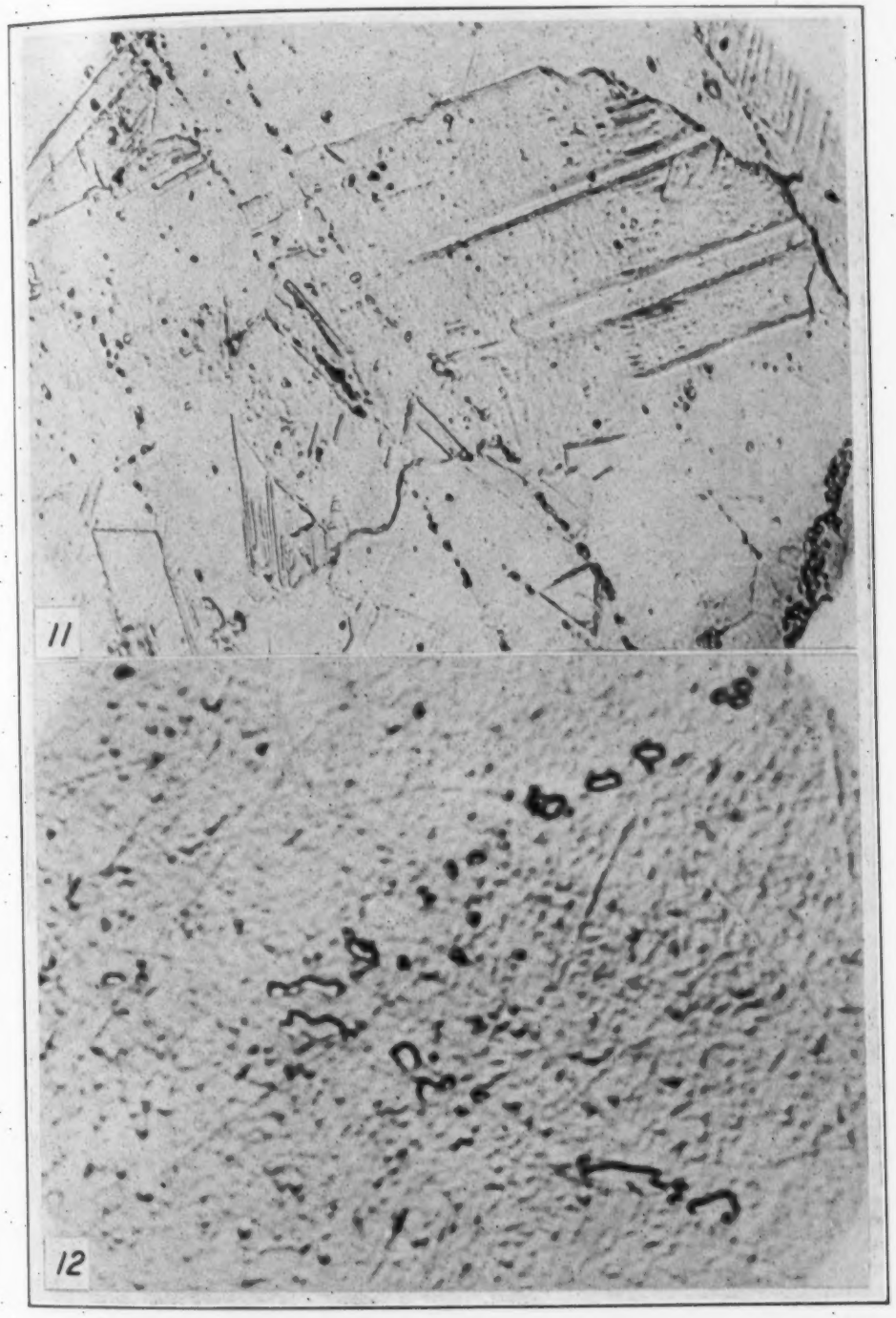
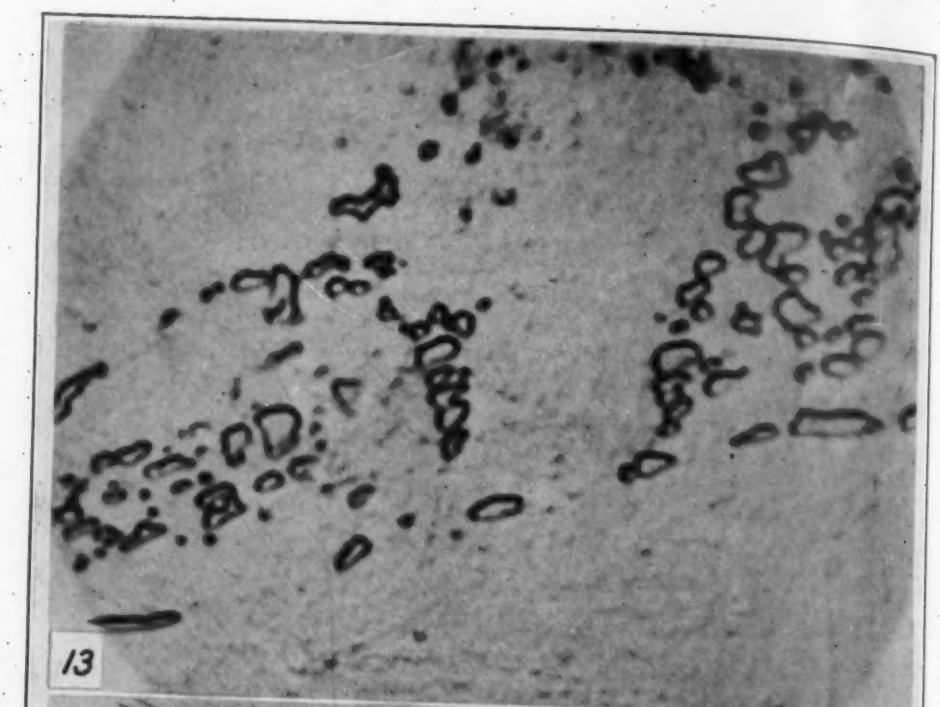


Fig. 11—Photomicrograph Showing Segregated Carbides Mostly Along Grain Boundaries. × 1000.

Fig. 12—Photomicrograph Showing Carbides Standing in Relief. × 3350.



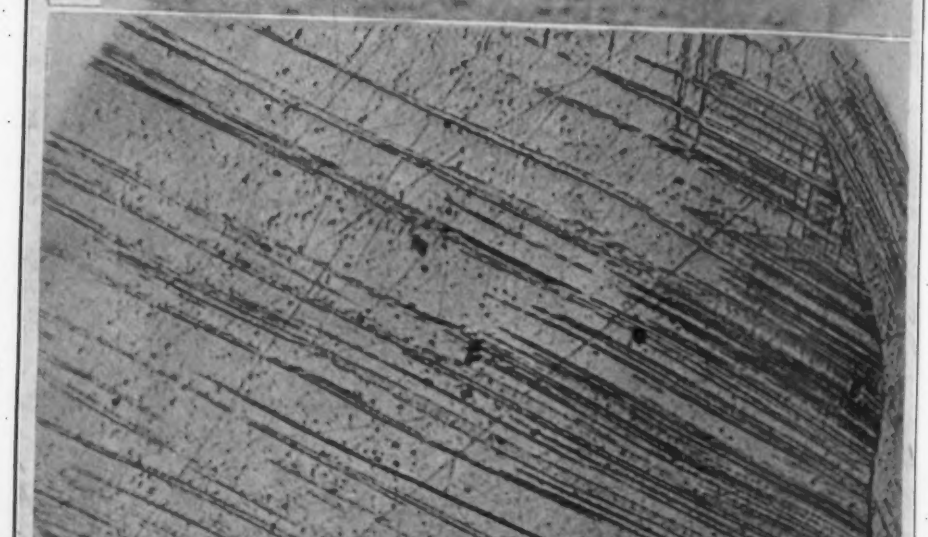


Fig. 13—Photomicrograph Showing Carbides Along a Grain Boundary and a Group Within the Grain. The Material that Appears Almost as a Dark Cloud in Fig. 7 is Represented here as Coagulated Masses. These Particles Stood out in Relief. Their Edges were Rounded in Polishing. × 3350.

Fig. 14—Photomicrograph Taken Near Base of Threads. The Slip Planes in N7 were Less Regular and Less Frequent than Those Found in N11. This Indicates Greater Rigidity of Material Within the Grain in N7. × 1000.

fening of the austenitic grains than to a weakening of bonding at grain boundaries.

The stiffening seems to have been caused by the interference with slip along atomic planes in the austenitic grains. There is strong direct and indirect evidence that carbides, probably chrome carbides, are precipitated within the grains, and that this precipitation is brought about by mechanical working of the metal. This precipitation seems also to be associated with a critical point that is found at 1330 degrees Fahr. (720 degrees Cent.) on heating. Just how these are related is not clear. The critical point found may be the A_1 point. The A_1 thermal arrest, on cooling, has been regarded as the point where carbon-saturated austenite changes to pearlite. On heating it should conversely mark the point where pearlite changes to saturated austenite. The writer confesses to some difficulty in visualizing this as a reversible transformation even in a plain carbon steel. In the present instance the explanation is the more difficult because the metal being austenitic at room temperature there is no chance for ferrite to change to austenite even though there were pearlitic grains present, which there are not.

The metal at room temperature seems to be wholly austenitic. However, the austenite may not be stable,* and may tend to change to ferrite on moderate heating. Such ferrite would undergo transformation at the A_3 point and explain a thermal arrest on heating but not a precipitation of carbides. Carbides should in fact be absorbed. It would not be easy to reconcile this idea with the arrest found on cooling since there would be no more reason for part of the metal to transform from austenite to ferrite than for most of it to so change and the metal admittedly is austenitic at room temperature. The point found could be a gamma-delta transformation except for the fact that in both specimens the evidence of slip planes indicate that the metal was austenitic at the temperatures of the tensile tests both of which were above the critical temperature. In view of the above difficulties in the reconciliation of experimental evidence the writer is inclined to regard the critical point found as an A_1 point, the significance of which he does not understand.

Other features of the investigation do not present such difficulties. The more ductile specimen necked down at the rupture and in the most deformed part the metal was evidently ferrite. It would

*This idea was suggested to the writer by M. A. Grossmann in a discussion of the above experiments.

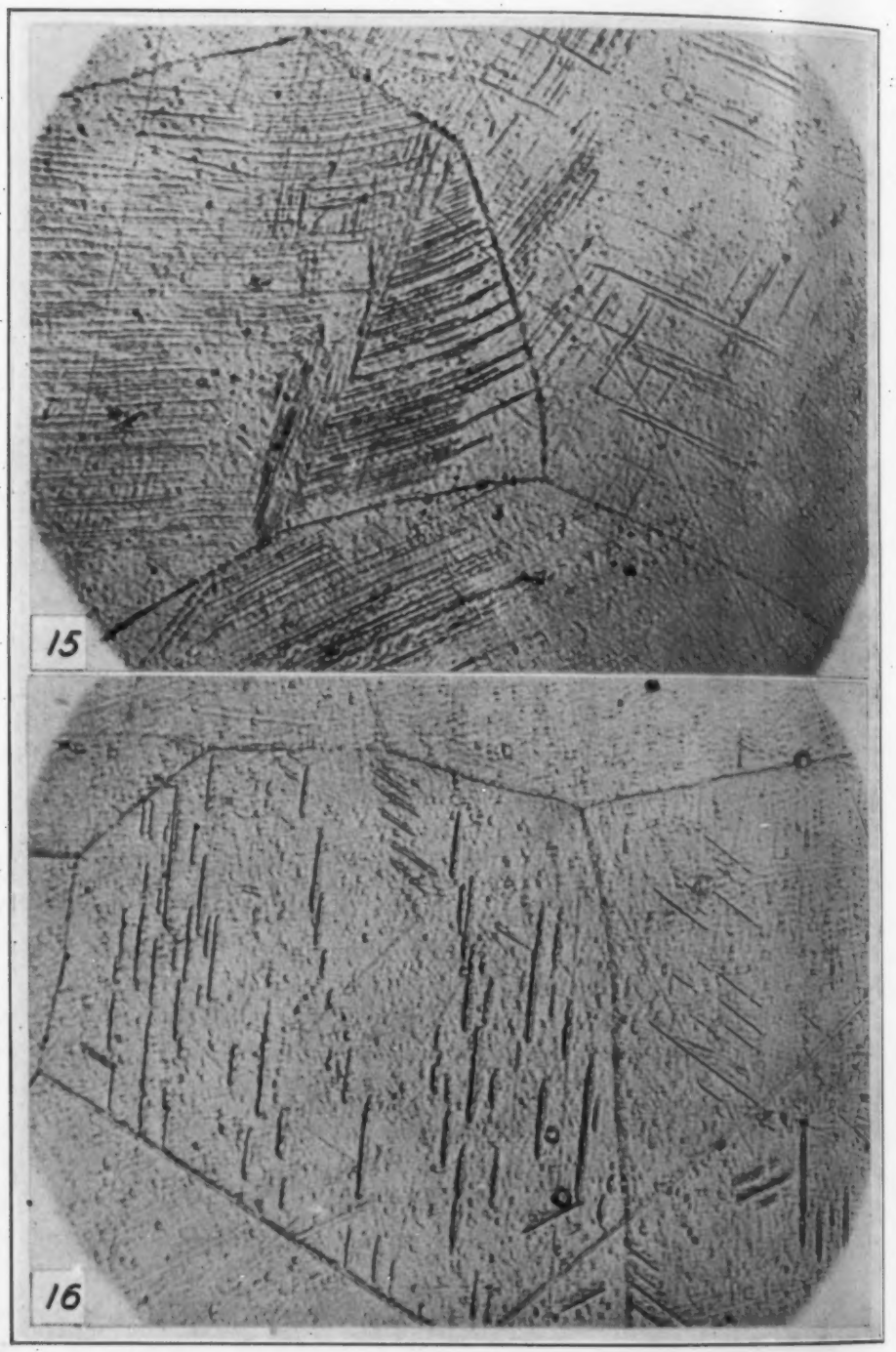


Fig. 15—Photomicrograph Taken Near Base of Threads. Note Curved Slip Lines. This Grain was Well Distorted Before Slip Started. × 1000.

Fig. 16—Photomicrograph Showing Structure Somewhat More Remote from Threads. Near Middle Slips were Infrequent. × 1000.

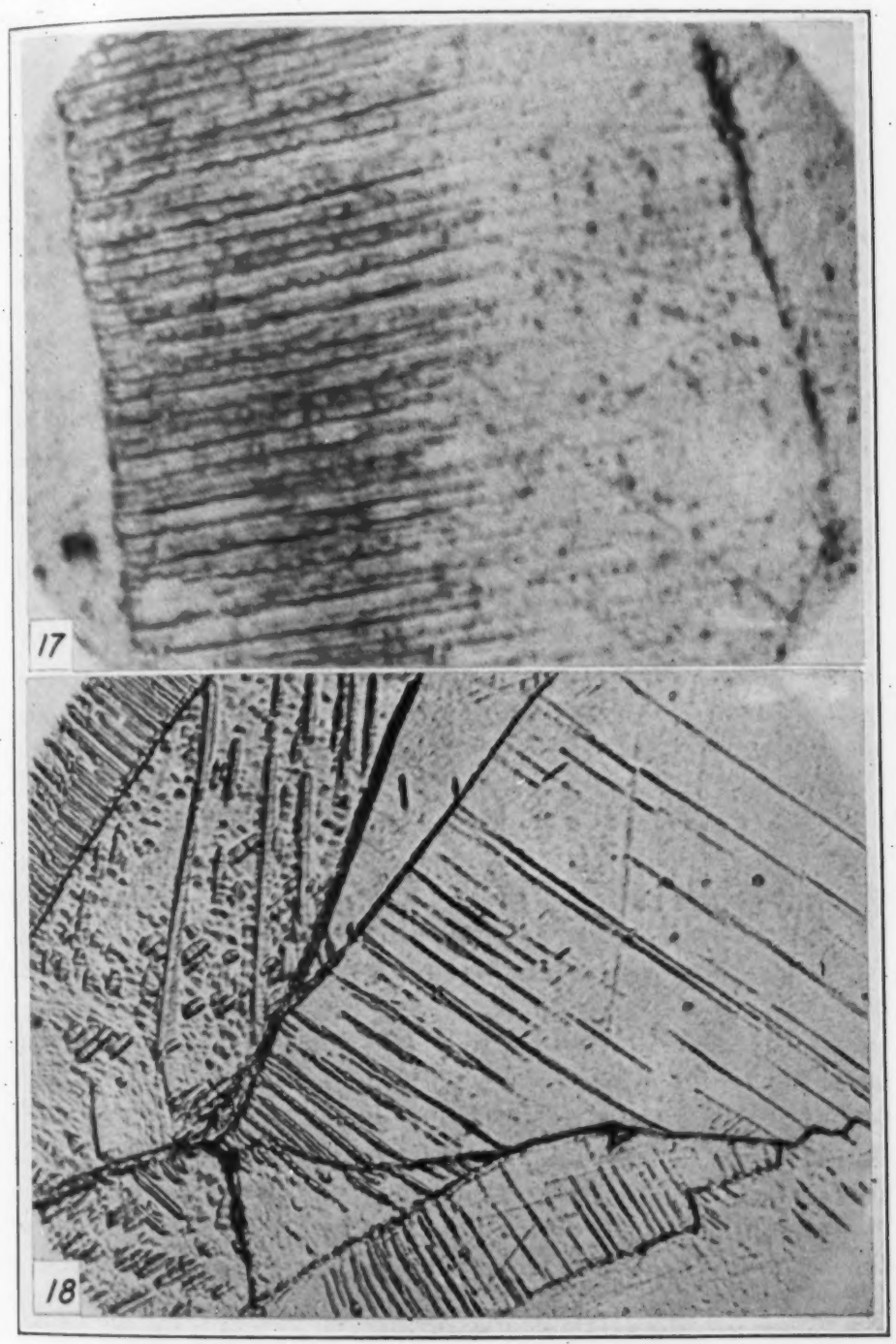


Fig. 17—Photomicrograph Taken from a Point in the A Section of N7. Note Irregular Slip Lines. These Slip Plane Pictures Illustrate Some of the Boundary Irregularities Noted. The Jagged Boundary Lines Were in Many Cases Caused by Jutting out Blocks of Slipped Material. × 3350.

Fig. 18—Photomicrograph Showing Peculiar Slips in Region Toward Ruptured End of N7. × 1000.

appear, as has been suggested, that the austenite is unstable, and, though it does not change readily to ferrite on heating, it does change upon mechanical working at temperatures above room temperature.

With this idea in mind the stiffening of the grains of the less ductile specimen is readily accounted for. Evidently upon mechanical work ferrite grains, of submicroscopic dimensions are formed along planes in the austenite normally favorable to slip. These grains would themselves tend to stiffen the metal. They also tend to reject carbon from solution because of their lowered solubility for carbon. The carbon is precipitated probably as practically amorphous carbide. These small particles serve further to stiffen the grains. During mechanical working they tend to migrate to regions of less stress intensity and in doing so form aggregates in some cases within the grains, but more frequently as broad borders along grain boundaries. It is recognized that from the present evidence the carbon may have been precipitated as carbon and may have aggregated as carbon. It is regarded, however, as more probable that carbides would be formed.

The evidence of the slip planes supports the idea that obstructing material was precipitated along atomic planes. The N7 specimen showed a greater number of slips than did the N11, but the individual slips were of less magnitude.

This observation suggests the mechanism of work hardening of these specimens. Under the influence of slight deformation precipitation occurs along any plane that starts to slip. The movement for this reason does not proceed far, the deformation being transferred immediately to a neighboring plane. Any initial tendency to neck down would cause an excessive carbide precipitation with consequent greater hardening and a rapid transfer of deformation to other parts of the specimen. This rapid transfer of deformation would cause the specimen to pull down uniformly without sensible necking. The grains should be stiffened and consequently strengthened until the body of the grain would show greater strength than that of the bonding between grains. Rupture should finally occur along grain boundaries giving a typical crystalline fracture. The facts of the experiments are quite consistent with this idea of grain stiffening. The fracture was crystalline and in addition there were numerous partial ruptures along grain boundaries in the vicinity of

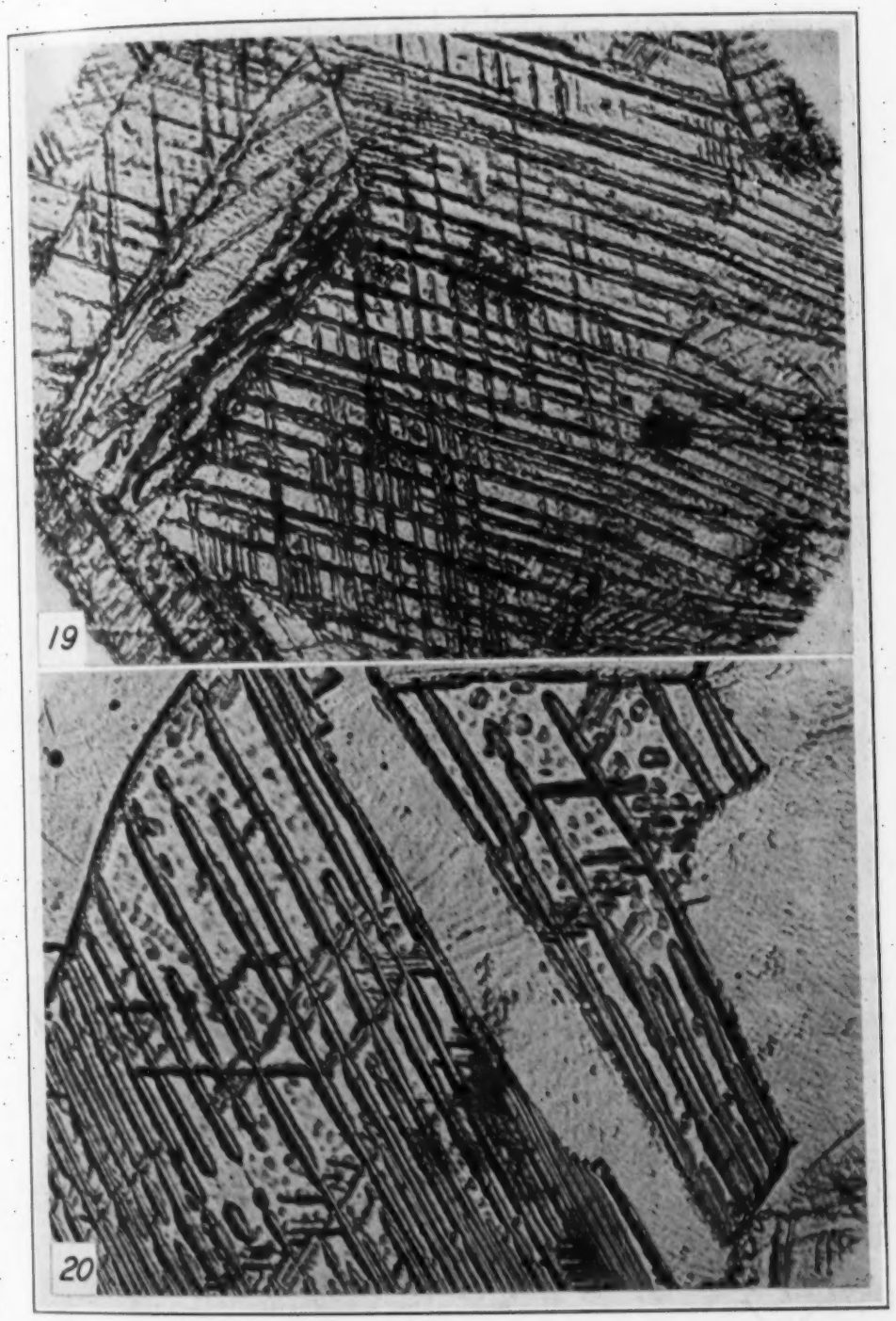


Fig. 19—Photomicrograph Taken from Region Near Base of Threads. Compare with Figs. 14 an 15. Note Greater Number of Slip Lines. Cross Slips are Frequent, the Lines are Straighter and More Complete than in N7. × 1000.

Fig. 20—Photomicrograph Taken from a Point in the B Section of N11. Note Regularity of Slip Lines and Fact of Broad Etching. × 1000.

the break. Careful examination indicated that most of the fracture was along grain boundaries.

In the N11 specimen as stated above typical necking was observed. In this case the high temperature was above that at which marked work hardening occurs. Ferrite is formed and carbides are precipitated, but these seem to form coagulated masses immediately and have little effect in hardening the material. As a consequence there is no rapid transfer of deformation such as occurs at a lower temperature. Most of the deformation occurs very close to the rupture and the body of the specimen is affected relatively less than it would be at a lower temperature where necking does not occur. While estimations of the carbide precipitated in the two cases is not possible it is quite likely that there is a greater precipitation of carbide at the lower than at the higher temperature due to a possibly greater volume of deformed metal at the lower temperature.

The question of the relation of the critical point found to the ferrite and carbide precipitation has not been disposed of. Perhaps the relation is fortuitous. In metal containing 2 per cent silicon, 18 per cent chromium, and 9 per cent nickel, only a feeble thermal arrest occurred but the brittle range developed. In steel containing 2.25 per cent silicon, 9 per cent nickel, 20 per cent chromium, and 3.7 per cent tungsten, no indication of a thermal arrest was found, but here too the brittle range developed and at the same temperature as in the other materials.

In these cases the metal used for the thermal curve had not been worked at temperature. It is assumed that there had been no precipitation of carbide. When the metal was worked at elevated temperatures according to our theory, ferrite should have been formed and carbides precipitated and the characteristic brittle range developed. This behavior is consistent with the ideas expressed above if we consider that the presence of the silicon and the tungsten rendered the austenite somewhat more stable so that whereas some ferrite was present or was formed in the material of the present tests, due to the effect of temperature alone no ferrite existed or was formed in the other two materials because of the fact that the metal was not worked. If this explanation is accepted, then the brittleness observed is actually connected with the critical point because when no carbides were precipitated no critical points were found.

The predominating austenitic structure seems to be unstable to an extent that mechanical work can change it to a more stable ferrite.

It seems hardly probable that the metal develops this instability at an elevated temperature. It is more probable that such instability exists from the beginning and that the austenite is really more unstable at lower than it is at higher temperatures.

Ferrite and carbides would under this conception be precipitated at low, possibly at room temperature.* These precipitated particles probably of colloidal magnitude would not greatly modify ductility till they had achieved a critical size. This critical value seems to occur close to the critical temperature.

Acknowledgements

This investigation was carried out at the suggestion of Colonel T. C. Dickson, Commanding Officer and Director of the Laboratory, whose encouragement and active co-operation made the study possible. Thanks are due also to Miss M. R. Norton for most of the mechanical work in preparing specimens and illustrations. Material used was supplied by the Carpenter Steel Company.

DISCUSSION

Written Discussion: By Albert Sauveur, Harvard University, Cambridge, Mass.

The subject of Dr. Lester's paper is one that must command the attention of steel metallurgists because of the increasing importance and use of nickel-chromium austenitic steel and he is to be complimented for the ability with which he has dealt with it.

I shall venture to suggest that if Dr. Lester had selected for the title of his paper "The Range of Reduced Ductility in 18 and 8 Chromium-nickel Iron—" instead of referring to a "brittle range," it would have been in closer agreement with the facts, as we can hardly describe as brittle at 1290 degrees Fahr. (700 degrees Cent.) a metal which at that temperature has an elongation in two inches of some 50 per cent and a reduction of area of some 52 per cent.

That steel of the 18-8 type exhibits a reduced ductility in the range of 1290 degrees Fahr. (700 degrees Cent.) is now a well recognized fact. It has been clearly brought out by B. Strauss and others. That such fall of ductility does not correspond to an increase of strength appears to me worthy of careful consideration. Some recent twisting tests performed at Harvard University confirm this peculiarity. The theory Dr. Lester advances to explain the phenomenon under investigation is undoubtedly the result of careful thinking on his part and deserves the same treatment from his critics. If the occurrence is to be explained, in part at least, in the light of the dispersion theory, should we

*This concept was not entertained at first but was adopted because of results obtained by Dr. R. H. Aborn of Harvard University, which indicate the presence of finely divided ferrite after working the metal at low temperatures. His results will be published shortly.

not expect that the precipitation of carbides should increase the strength as well as decrease the ductility? Again it is well to bear in mind that we are dealing with an alloy containing but 0.095 per cent carbon, which precludes the formation of much carbide. If in the form of Fe_3C we could not have more than 1.50 per cent of it, while if it is present as Cr_4C, the lowest chromium carbide so far reported, I believe, we could not have more than 1.8 per cent. The formation of ferrite grains of submicroscopic dimensions should also increase the strength.

Dr. Lester writes that "carbides are precipitated and that these tend to travel to grain boundaries under the influence of strain in the metal." Such migration should require time and should not take place in dynamic testing.

Written Discussion: By M. A. Grossmann, Central Alloy Steel Corp., Massillon, Ohio.

The paper by Dr. Lester brings to light a number of interesting facts about the austenitic chromium-nickel irons.

It is believed that the facts will in general accord with the belief expressed by Dr. Lester on page 755, namely that the phenomena are due in the main to an Ac_1 point between 1300 and 1400 degrees Fahr. (700 to 760 degrees Cent.).

On page 746 reference is made to Figs. 6 and 7 where numerous dark specks are found upon etching. Dr. Lester's view seems reasonable, that "each black speck is regarded as made up of an agglomeration of still finer ones." It seems proper to assume that these black regions correspond somewhat in their nature to the "troostitic" patches found by Krivobok[1] in deformed and reheated austenitic manganese steels. This would assume that the dark spots of Lester's Figs. 6 and 7 are agglomerates of carbide and alpha iron.

On page 748, paragraph 3, it is stated that the particles in Figs. 12 and 13 polish in relief and are white under the microscope. These particles would appear to be solid carbides, and inasmuch as they are found at the temperature of 1800 degrees Fahr. (980 degrees Cent.), it would appear that they are the free carbides sometimes found in austenitic steels of this nature. In other words the difference between Figs. 6 and 7 on the one hand, and 12 and 13 on the other hand, is that the particles of Figs. 6 and 7 include some alpha iron (ferrite), whereas the particles of Figs. 12 and 13 are solid carbide.

The view that the phenomenon at 1400 degrees Fahr. (760 degrees Cent.) is a precipitation of alpha iron leads to agreement with numerous conclusions drawn by Dr. Lester. Among these are (1) his statement that the loss of ductility is ascribed to a stiffening of the austenitic grains due to precipitation of alpha iron, (2) the critical point corresponds to the temperature at which pearlite changes to austenite (or rather alpha iron to gamma iron), and (3) the fact that the deformation is carried on at the A_1 temperature gives opportunity for the alpha iron particles to grow during the deformation and make their appearance microscopically.

It should be observed that steels of this type can be rendered completely austenitic again by a quench from 2100 degrees Fahr. (1150 degrees Cent.). If the temperature is lower than 2100 degrees Fahr. (1150 degrees Cent.), the absorption of carbides is not complete. This could explain the fact that the

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[1]V. N. Krivobok, "A Study on the Constitution of High Manganese Steels"—TRANSACTIONS, American Society for Steel Treating, June 1929, p. 893.

critical point appears not only on heating but also on cooling, because the heating curve of Lester's Fig. 2 indicates that the sample was heated to only about 1650 degrees Fahr. (900 degrees Cent.). The minute quantities of alpha iron transform to gamma iron upon passing through the 1400-degree Fahr. transformation, but such gamma iron does not absorb all the carbides and become completely absorbed in the rest of the austenite matrix until a temperature of about 2100 degrees Fahr. (1150 degrees Cent.) is reached. If, as in this case, the heating temperature is only 1650 degrees Fahr. (900 degrees Cent.), the minute gamma iron grains remain poor in chromium carbide, and therefore revert to alpha iron at the Ar_1 point when cooled, because they are very unstable.

Written Discussion: By R. L. Duff, Standard Oil Development Co., Elizabeth, N. J.

Dr. Lester is to be congratulated on his excellent presentation. The explanation given for the loss of ductility in these steels, backed up by the photomicrographs, is in agreement with investigations along similar lines which we have been connected with.

While we are not prepared to enter any formal discussion on the paper at this time, there is one point which we are not entirely in agreement with. We refer to the use of the term, "brittleness." In the abstract it is stated the steel becomes relatively brittle when heated to about 1300 degrees Fahr. This appears to us as being misleading in view of the fact that Fig. 1 shows the steel to have an elongation and reduction of area of about 50 per cent at this temperature.

Written Discussion: By V. O. Homerberg, Massachusetts Institute of Technology, Cambridge, Mass.

I hope that Dr. Lester will extend his investigation to include tensile tests at room temperature on specimens which have been previously reheated within the same range of temperature as recorded in his paper. The results of Izod or Charpy tests should be included.

The author's results are based on the use of material containing approximately 0.10 per cent carbon. Since it is generally believed that the embrittlement is due to the precipitation of carbides and their presence at the grain boundaries, then material containing a lower carbon content should show a less tendency toward embrittlement. I hope that material containing not over 0.06 per cent carbon will be tested in a manner similar to that used in the present investigation.

Mr. Edlund[2] has determined the Izod values of a chrome-nickel iron containing 0.06 per cent carbon. Specimens were tested both in the original condition and after heat treating. Various quenching and tempering temperatures were used, the latter to cover the range between 200 and 1450 degrees Fahr. The time of tempering was four hours in most cases, eight hours being employed in a number of instances. All tests were made at room temperature. His results show no evidence of embrittlement. It is possible that the time at the tempering temperature was too short to cause the precipitation of the carbides, if such an occurrence takes place in material of this carbon content. Dr. Lester's observations were made on specimens which were under stress while

[2]Metallurgist at the Ludlum Steel Company. Private communication.

at temperature. If the effect of work greatly facilitates the precipitation of the carbides, then the heating alone may have to be greatly prolonged to obtain similar results.

The author has hinted that the thermal arrest might be a gamma-delta transformation or that the austenite was unstable and tended to change to ferrite on moderate heating. Have any results been obtained by an X-ray examination to show whether or not gamma iron alone is present under these conditions?

Although the presence of carbides was not detected at many of the grain boundaries, this fact does not necessarily prove that they are absent since it would be practically impossible to detect their presence, even at high magnification, if the particles are very minute or submicroscopic in character.

I cannot conceive of the possibility of an A_1 point in this material since it is entirely austenitic at room temperature.

Written Discussion: By John R. Freeman, Jr., U. S. Bureau of Standards, Washington, D. C.

The curves shown in Fig. 1 of Dr. Lester's paper are very interesting. They show that the ductility of this steel decreases in the temperature range 1200 to about 1500 degrees Fahr., the elongation and reduction of area at the latter temperature being less than at normal atmospheric temperatures. It is of interest to point out that a brittle range of temperature of this type is more common than generally understood to exist.

In studies which Mr. Quick and I have been making at the Bureau of Standards of the tensile properties of rail and some other steels we have found this phenomena to exist to a more or less marked degree in rail steels, Armco iron, a one per cent carbon steel and some alloy steels. A few typical curves are shown in the following figures. Fig. 1 shows the type of curve obtained on two distinct heats of a rail steel. In some cases a more marked inversion of the ductility curves occurs while in others it is less pronounced. Fig. 2 shows curves obtained on Armco iron by the independent observers.[3, 4] You will note that the phenomenon is quite distinct from the well known blue heat range occuring at 390 to 570 degrees Fahr. (200 to 300 degrees Cent.) and also the hot short range commonly associated with the A_3 transformation. We have given the term, "secondary brittleness," to the phenomenon in order to distinguish it from the blue heat brittleness. The temperature range in which secondary brittleness occurs appears to vary from heat to heat and markedly in degree.

Some of the earlier investigators in the studies of steel at elevated temperatures have found evidence of it. Data presented by Welter[5] in Germany in 1921 indicated its presence. Dupuy[6] in France also in 1921 found secondary brittleness in a 0.90 per cent carbon steel. Figs. 3a and 3b are taken from their work.

[3]Rawdon and Berglund—"Unusual Features in the Microstructure of Ferrite," Bureau of Standards Scientific Paper No. 571, p. 698, Fig. 3b.

[4]Inokuty, T., "Tensile Strength of Steel at High Temperatures," Science Reports of Tohoku Imperial University, July, 1928.

[5]Welter, G., "Elastizität und Festigheit von Spezial Stahlen bei hohen Temperaturen." Forschungsarbeiten a. d. Gebiete d. Ingenieurswesen, Vol. 230, 1921, p. 1.

[6]Dupuy, E., "Researches Experimentales sur les Propriétés Mecaniques des Acier aux Temperatures Élévés," *Revue de Metallurgie*, Vol. 18, 1921, p. 331.

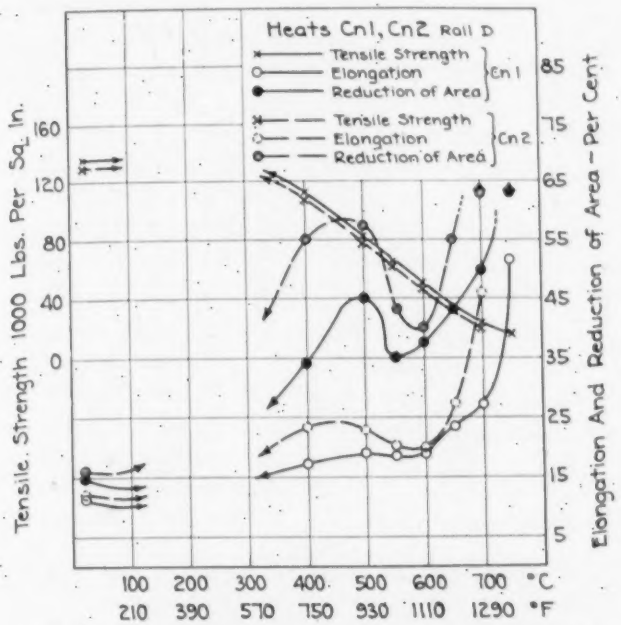

Fig. 1—Curves Obtained on Two Heats of Rail Steel.

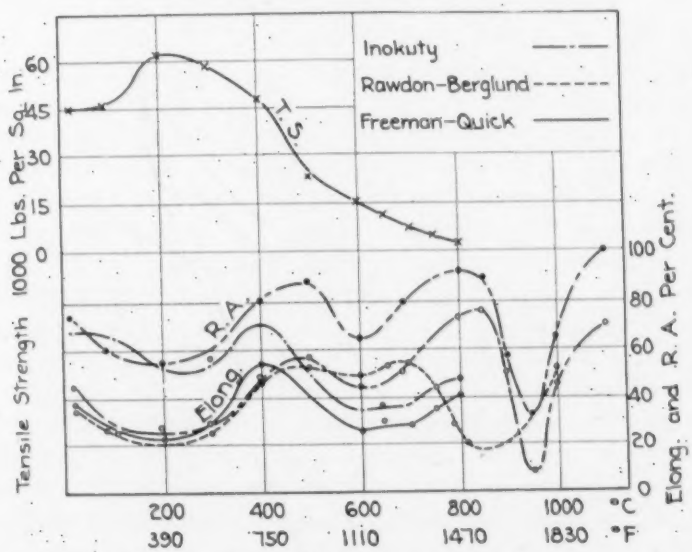

Fig. 2—Curves Obtained on Armco Iron.

Welter carried his tests only up to 930 degrees Fahr. (500 degrees Cent.) but it is evident that the ductility is decreasing rapidly and he made a passing comment on it.

We do not propose to present a discussion at this time of the significance of "secondary brittleness" and its relation to certain types of failures but hope to present a full detailed report of our findings in the Bureau of Standards Journal of Research in the near future. We are very pleased to have this information presented by Dr. Lester and thought it would be of interest to him

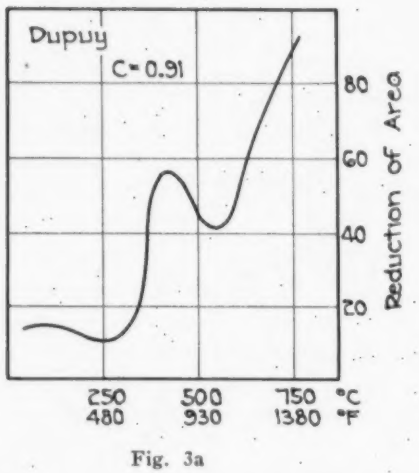

Fig. 3a

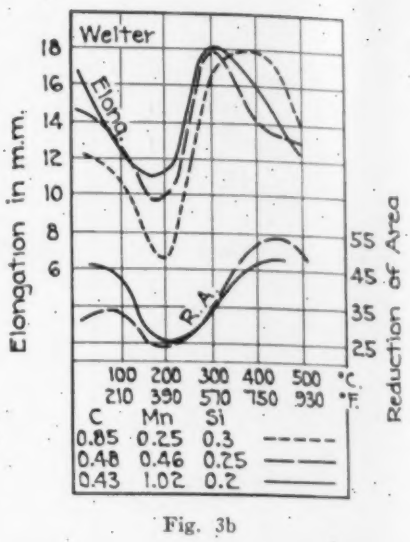

Fig. 3b

and the members of the society to know of the work we have been doing.

Written Discussion: By R. H. Aborn, Engineering School of Harvard University, Cambridge, Mass.

Dr. Lester's paper is very timely, coming as it does with the broad development and marketing of 18-8 steels. Portions of the metallographic evidence recall to mind some of the pioneer work of Bain and Griffiths[7] in this field, as presented in their paper.

The work referred to in a subscript of Dr. Lester's paper was undertaken several months ago in connection with torsion tests, such as described in Dr. Sauveur's Campbell Memorial Lecture. In view of the relatively high strength of this steel at room temperature, it seemed logical to expect an appreciable amount of martensitic formation as a result of twisting. In addition to microscopic examination, X-ray analysis was employed as the most efficient means of detecting the presence of alpha iron. The specimen[8] was so placed that the beam was incident on the surface layers, which, of course, in a torsion specimen are the most severely worked.

To our surprise, we found that apparently almost two-thirds of the iron had transformed to the alpha phase, as estimated by the relative intensity of comparable lines. Neither gamma nor alpha lines gave resolution of the doublet, and in addition the alpha lines were very broad, indicating, probably, severely distorted alpha crystals of minute size and varying lattice dimensions. To determine whether this condition applied to the surface layers only, the specimen was reduced by etching to two-thirds of its original diameter (0.250 inch) and again examined, with substantially the same results.

[7] "An Introduction to the Iron-Chromium-Nickel System," *Transactions*, A. I. M. E., Vol. 75, 1927, p. 166.

[8] Analysis as follows:—

	Per Cent		Per Cent
Carbon	0.09	Phosphorus	0.022
Manganese	0.35	Silicon	0.36
Sulphur	0.014	Nickel	8.61
		Chromium	17.67

Work is in progress now on the examination of several austenitic steels covering a twisting range of temperature up to 1200 or 1300 degrees Cent. and the results will be published shortly in detail. It is of interest here, however, to state that when this steel is twisted at successively higher temperatures the proportion of alpha iron formed diminishes until at 600 degrees Cent. the ratio of alpha to gamma is practically the reverse of what it is at room temperature. At this temperature, furthermore, the doublet has reached the stage of resolution in the alpha lines. This may well indicate a critical size of alpha crystals to which Dr. Lester refers.

Written Discussion: By Edgar C. Bain, Research Laboratories, U. S. Steel Corp., Kearney, N. J.

Dr. Lester has contributed to the knowledge of the properties of the austenitic nickel rustless iron in a very valuable manner. He is to be complimented upon his paper.

There is some reasonable doubt that the phenomenon discussed by Dr. Lester should be called a "brittle range." The alloy suffers a loss in ductility as a result of prolonged heating in a wide range of temperature following or accompanied by some deformation but the term "brittle range" has already been used in a somewhat different sense and it may be well to designate the effect by another phrase.

The behavior of the nickel rustless irons has been long known to fall into a very definite broad classification represented by Hadfield's manganese steel and the iron nickel alloys. It is the familiar decomposition of unstable austenite. W. E. Griffiths and the present writer briefly discussed this phenomenon in their A. I. M. E. paper (presented in February, 1927) and showed a photomicrograph of the separation of carbide in cleavage plane distribution. It is the more interesting to us therefore to find Lester's corroborations. To quote: "A very long annealing treatment causes some precipitation of excess carbide in parallel planes within the grains, sometimes on two families of planes simultaneously, developing a mesh system on the polished section. In certain cases it appears at high magnification that these rejected plates may be laminated with ferrite when the carbon and nickel content is relatively low. This is distinct from the ordinary destruction of austenite which develops the chevron-like ferrite precipitation later described. Whether these austenitic alloys are all truly stable at room temperature is somewhat doubtful, for the atomic sluggishness is so great in any event that they cease to readjust themselves atomically or to restore equilibrium below temperatures probably as high as 300 degrees Cent. However, a method may be used to determine this fact with more certainty. If such specimens of austenite are severely deformed at room temperature, they may harden inordinately and become feebly magnetic in the manner of Hadfield manganese steel. If this happens, then obviously the austenite is not truly stable at room temperature and the atomic agitation of cold work suffices in a small way to develop the truly stable form of ferrite. Certain specimens in the iron-chromium rich austenites showed this tendency clearly. It is suggested

that a series of deformation experiments at various temperatures would determine the true transformation temperature of the alloys."

The apparent complexities of Dr. Lester's observations become somewhat more simple if one considers them as all resulting from the circumstance of an undercooled phase:—Undercooled as to allotropic transformation (austenite to ferrite) and supersaturated as to carbon. Both unstable conditions tend to revert to the stable form but do so at room temperature and below, and even at a few hundred degrees warmer, at an infinitesimal rate. The stable condition of this alloy at room temperature is, of course, essentially ferrite (plus carbide). Equilibrium can not be brought about except by atomic mobility supplied by elevated temperature or mechanical work or both. Many hundred hours may be required at even 600 degrees Cent. (1100 degrees Fahr.) to develop much ferrite (although at equilibrium it is probably at least half ferrite at this temperature), unless some agitation in the form of deformation is provided. Deformation alone is quite effective in causing the alloy to revert to ferrite at room temperature, as may be discovered by a magnet on any worked sample of the material. Above about 900 degrees Cent. (1650 degrees Fahr.) the alloy is always wholly stable austenite, except at very high temperatures at which ferrite is again evolved by the austenite—"delta iron" reaction. So much for the allotropic change in the undercooled austenite.

As for the supersaturation in carbon, it should be remembered that this variety of austenite shows very little carbon solubility. In the paper referred to above, it was mentioned that austenitic chromium-nickel-iron alloys showed considerable carbon precipitation with as little as 0.12 per cent carbon. Doubtless at 800 to 900 degrees Cent. (1475 to 1650 degrees Fahr.) carbide would ultimately separate from the alloy containing as little as 0.09 per cent carbon. At perhaps 1300 degrees Cent. (2375 degrees Fahr.) as much as 0.15 per cent carbon would certainly be dissolved. As usual, grain boundaries are the principal location of precipitated constituents even when intragranular precipitation occurs also. Carbide precipitation also suffers delay from the extreme sluggishness of these high alloy materials and again the precipitation is hastened by some deformation. In general the allotropic change takes precedent when equilibrium is restored at low temperature with considerable cold work and (if the alloy is rich enough in carbon) the carbon precipitation is the dominant reaction at the higher temperatures of reheating with little or no deformation. Carbide re-solution is accomplished most quickly by reheating to temperatures in the vicinity of 2150 degrees Fahr. (1175 degrees Cent.) even though the carbon content is sufficiently low to be absorbed entirely at a lower temperature.

Dr. Lester's data are well taken and are worthy of the attention of all interested in the rustless irons.

Author's Closure

Prof. Sauveur's criticism with regard to the title of this paper is well

taken. Perhaps it would have been better to refer to the brittleness found as reduced ductility. However, the fracture itself is that associated with brittleness. In the opinion of the writer the material that finally ruptured was really brittle. The reduction and elongation occurred in metal that was to a large extent in the original austenite condition. Fracture occurred after the metal had become largely ferritic. Had test specimens been taken in this transformed condition no doubt there would have been little reduction or elongation.

The point that the reduced ductility is not reflected in an increased strength is as Prof. Sauveur points out an interesting phenomenon and one worthy of further study. It seems to the writer that the tensile strength of this material as observed may be partly due to the intrinsic strength of the austenitic material and partly due to the stiffening effect of the minute ferrite crystals and the precipitated carbides. The contributions from the ferrite and the carbides build up in proportion to the deformation. On this view there might not be a sudden increase in strength although when the strength within the grain approaches the strength of the intergranular bonding there would be a sudden loss of ductility. The above explanation is suggested. It is realized that further study may develop a better one.

With regard to the last point of criticism that the carbide migration could not take place during the time of dynamic testing the writer can point only to the experimental evidence that such migration did occur. It is pointed out that the tensile tests on the material under discussion were carried out with a horizontal hydraulic testing machine, the elongation being measured with an extensometer. The time of testing is longer than would be the case with a motor-driven screw testing machine, and with a dial gage extensometer. The time for the individual tests was about 15 to 20 minutes. It is hoped that Prof Sauveur will extend the tests now in progress at Harvard to include microscopic examination to detect possible carbide migrations. His twisting tests, however, being of much shorter duration might, as he suggests, allow insufficient time for migration.

The writer would like to take this opportunity to acknowledge his indebtedness to Dr. Aborn for helpful criticism of the paper presented before it reached its final form. He suggested the idea of the ferrite formation and supplied the proof from his own work on material of similar composition. The writer is struck by the fact that the alpha doublets in Aborn's tests resolve for material tested at 600 degrees Cent. This temperature is not far removed from that at which the sudden change in ductility occurs. It would seem that the two phenomena are related. Such resolution might result from a coagulation of ferrite particles into crystals large enough to give sharp lined X-ray spectra. It might result also from the expulsion of carbon from supersaturated alpha crystals. In the latter case the observed precipitation of carbides would be fixed more or less definitely with regard to temperature. Such expulsion of carbon as carbide might account for the dark cloud effects of Figs. 6 and 7 that Grossmann suggests might be troostite.

The publication of Dr. Aborn's complete results will be looked forward to in the hope that further light may be thrown on this phenomenon.

Mr. Grossmann's idea that the black specks in Figs. 6 and 7 are agglomerates of carbide and alpha iron appeals to the writer as reasonable and probable. There seems to be too much of the darkened material for it to be altogether carbide. Perhaps we should, as he suggests, regard the masses as troostite where troostite is regarded as a mixture of alpha iron and uncoagulated carbide particles. In view of the X-ray results of Aborn the troostite may have formed subsequently to an agglomeration of alpha particles. However, it is difficult to picture the alpha particles as migrating, while it is reasonable to suppose that carbide particles would migrate.

With regard to Prof. Homerberg's suggestion that impact results of this material should be obtained the writer is in agreement. However, the experimental difficulties in the way of obtaining such results are very great. It is doubtful whether the value of the data is sufficient to justify the labor and expense involved in the measurements.

In his second point he seems to accept a generally prevalent view that carbides segregated at grain boundaries cause the loss of ductility. It is pointed out that the present experiments point to the fact that the carbides cause loss of ductility only when they are still within the grain and that when they are at grain boundaries there seems to be less tendency to cause brittleness. It is true that possibly they might be present at grain boundaries in submicroscopic particles. However, in such case their presence might still be evident because of the effect suggested by Grossmann, that is they would be precipitated together with some alpha iron and the agglomeration would be visible just as the black cloud effects are in Figs. 6 and 7. Since we have visible evidence of the presence of these, why not accept the logical deduction from that evidence, rather than manufacture a hypothetical film of invisible carbides?

With regard to the effect of lowered carbon content on loss of ductility the writer is of the opinion that the loss would be less. Whether or not it would entirely disappear is of course a matter to be settled by experiment. The effect of the carbide precipitation could be eliminated. There would still be the effect of the alpha iron formation.

The results obtained by Mr. Edlund of the Ludlum Steel Co., cited by Prof. Homerberg, are to be expected. So far as the writer is aware thermal treatment alone is not apt to cause carbide precipitation. The 18-8 composition seems to give a borderland steel. It tends to remain austenitic but will change to a more stable ferrite steel upon plastic deformation. It would be interesting to determine if this steel like some manganese steels will change over to the ferritic condition on very prolonged heating. It is suggested that in annealing to get alpha iron the cooling should be a matter of days rather than hours.

NONDESTRUCTIVE TESTING

By Elmer A. Sperry

Abstract

A method of nondestructive internal inspection has been developed that is applicable to all metals and alloys. Direct current of high amperage is passed through the specimen and any minute crack or inclusion produces a deviation in the axis of current flow. This deviation is detected and amplified to a value suitable for operating recording equipment.

This electric method of inspection is now in daily use on the railroads of the country, where it is sweeping the tracks clear of the menace of internal transverse fissures. The device has been successfully adapted to the inspection of a great variety of parts, such as new rails at the mill, bars, tubes, axles, boiler plate and welded joints.

MODERN mass production of parts, accompanied as it has been by a variety of developments in the heat treating and alloy-field, has made the need for a nondestructive yard stick for measuring the interior soundness of metals a most urgent one. It is highly desirable that such a method of inspection be positive, reliable, and applicable to all metals regardless of their magnetic properties. All internal shrinkage cracks, minute inclusions, fissures, etc., must be located; as also any external flaws, such as fatigue failures in axles on shafts. The system must lend itself to automatic recording in order that the human element may be reduced to a minimum and a permanent ink record of the internal condition of every specimen made available for future reference.

History of the Development

For the past twenty years a number of independent investigators have been working on various methods of nondestructive inspection, based upon the action of direct or alternating magnetic flux passed through the specimen.

A paper presented before the Eleventh Annual Convention of the society, Cleveland, September 9 to 13, 1929. The author, Elmer A. Sperry, is president of the Sperry Development Company, Inc., Brooklyn, N. Y. Manuscript received May 31, 1929.

The magnetic permeability of steel varies widely with any change in its hardness, chemical content, heat treatment and any mechanical stress to which it may be subjected. The magnitude of these various factors is frequently far greater than that of a serious internal fracture.

This is brought out in the following excerpt from a report by the Bureau of Standards.[1]

> "In most, if not all, of the cases in which this method (magnetic) has been tried it has been found that influences having a negligible effect on the mechanical properties may modify the magnetic properties to a marked degree. For general application, therefore, this method in its present stage of development fails from the standpoint of reliability."

As late as January of this year, R. L. Sanford of the Bureau of Standards stated:[2]

> "Another lesson that has been learned is that it is generally not safe to draw too definite conclusions from the results of correlating magnetic properties with heat treatment alone, for we can never be assured that some accidental factor has not entered into the heat treatment and thus produced mechanical properties not normally associated with the specified heat treatment."

The use of alternating magnetic flux is even less promising than direct flux. It has all of the faults of direct flux, and in addition it is bound by the well known laws of skin effect. As may be seen from Table I the alternating flux is forced to remain in the outer skin of the specimen and therefore inspection by this process is of necessity superficial in so far as internal separations or cracks are concerned.

Method of Attack

After considering the work that had been done in the past, together with the results accomplished as related in the above paragraphs, the method of procedure seemed obvious. Why not use something that would travel easily in metals regardless of their magnetic properties, but that simply could not leap a chasm even though that chasm were but a molecule wide? Why not

[1]Bureau of Standards, "Magnetic Analysis," letter circular LC 173, August 1, 1925.

[2]Raymond L. Sanford, "Magnetic Analysis," *Journal*, American Institute of Electrical Engineers, January, 1929, p. 7.

use low voltage electricity and simply soak the specimen with current until it had to cough up the skeletons in its closet?

As between direct current and alternating current there could be but one choice where the entire cross section was to be examined. Alternating current distribution is governed by the laws of skin effect, the same as alternating flux (see Table I), and therefore the decision was made to use direct current.

Table I
Skin Effect in a 90-Pound Rail.

Frequency—25 cycles. Permeability 506.6 gausses/gilberts per cm.
Conductivity = 0.00005 ABMHO/sq. cm.
From Kenelly, Archard and Dana, Journal, Franklin Institute, August, 1916.

Layers Below Surface in Millimeters	Current Density Per Cent	Flux Density Per Cent
Surface	100	100
1	61	37
2	37	13
3	22	5
4	13	
5	8	
6	5	
7	3	

It was thought that if the specimen, such, for instance, as a railroad rail, were sound and homogeneous the current flow would be uniform and unobstructed, but if there were a flaw, such as a shatter crack, inclusion, or noncontinuity of any nature, the current flow would certainly be compelled to pass around the interruption and join forces again on the other side. This situation was seized upon in various ways to give positive indications not only of the exact location of the flaw, but also its size. Two of these may be briefly explained as follows:

(1) The uniformity of potential drop that exists at all other points of the rail is here interrupted, and, although the disturbance is minute, through amplification, it is brought up to usable magnitudes to operate indicators or recorders, paint spray, etc.

(2) In a sound rail the direction of current flow is axial unless disturbed. The slightest disturbance changes this alignment of flow, and means have been found to utilize this deviation, both as to angle and magnitude of mean axial departure, for giving an accurate interpretation of the cause,

especially when all elements are duly magnified so as to be recognizable. Thus the size, characteristic and exact location of the fissure or other flaw are accurately determined. This latter method has an advantage over the first, inasmuch as the indications and determinations are all realized without actual physical contact with the surface of the rail or other form of metallic conductor being investigated.

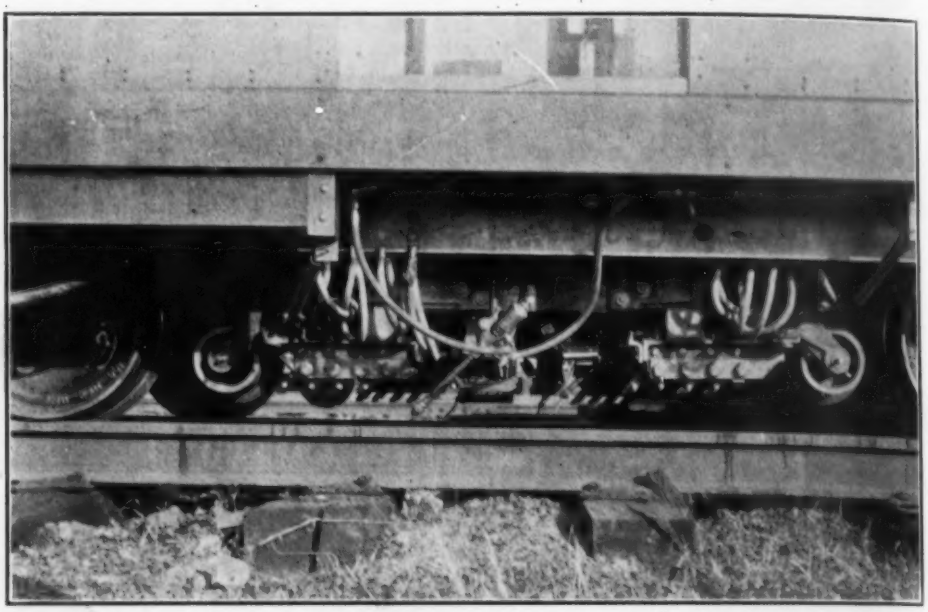

Fig. 1—Photograph Showing the Main Brushes in Contact with the Track.

One of the difficulties immediately foreseen was that of neutralizing inevitable variations, either large or small, in the primary or energizing current and thereby preventing false indications. So the original plan developed incorporated means to this end, completely neutralizing all such variations regardless of their magnitude and preventing them from reaching the interpretive portion of the equipment. Thereby the exploration method itself was confined to exact conformity with the interior characteristics. This was found comparatively easy of accomplishment, and may be illustrated by one method as follows:

The main primary energizing current is made to traverse the rail, or a section thereof, as by main brushes such as are shown in Fig. 1, in contact with the track. Intermediate between these brushes are located the three searching brushes 11, 12 and 13, shown in Fig. 2. These are connected to two opposite primary

coils 22 and 23, constituting the primary of a transformer 24. These coils are oppositely wound and produce opposite magnetic excitation of the transformer. All variations in the primary current will be picked up by the two outer brushes, and thus be completely neutralized as to their influence on the secondary 25, but in passing along the track, when a fissure occurs between one end brush and the middle brush the first coil 22 will become excited to a greater extent than the other. The transformer will become

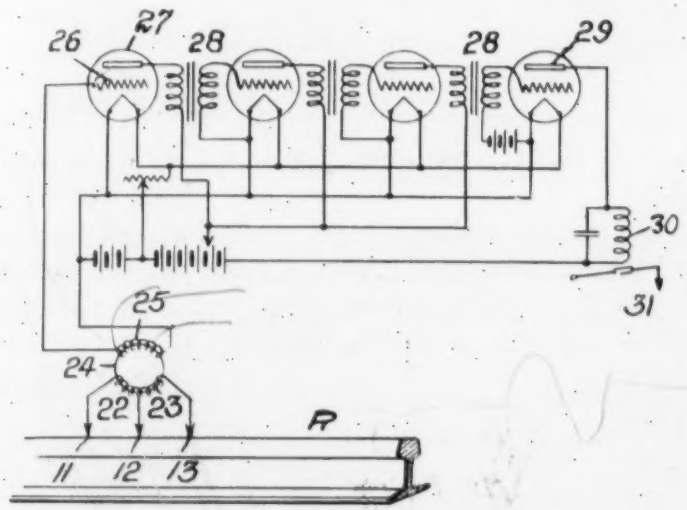

Fig. 2—Diagram Showing the Three Searching Brushes. 11, 12 and 13.

active and in the secondary will be induced half, say the positive side, of a sine wave curve, but in the next instant the fissure passes between the middle and the rear brushes, giving an opposite excitation to the secondary, completing the alternating wave by adding the negative side. We now have a true alternating wave. This wave then passes to the amplifiers and may be examined as to both its magnitude and characteristics, but it will be seen that any amount of variation in the primary exciting current can in no way reach the secondary, and therefore its effects are entirely neutralized.

First Practical Application

In October, 1911, the first serious accident occurred on the Lehigh Valley railroad, directly traceable to a transverse fissure which had grown to the point where the rail broke in service. This called the attention of all the railway companies seriously to

the possibility that their tracks might also contain these fissures, and it was at once found that they did. The Bureau of Standards in Washington was asked to undertake investigations regarding these fissures and especially with regard to finding methods for accurate location of the fissures and determining their size as they exist in track, with a view to sweeping our tracks clear of this menace. Other fatal accidents followed from transverse fissures in rails, and Dr. P. H. Dudley of the New York Central and Dr. Unger of the Carnegie Steel Works in Pittsburgh undertook intensive investigations, running parallel with those of the Bureau of Standards. Statistics indicate that in the course of this work some 700 rails were broken up without either the definite location or discovery of transverse fissures where they were supposed to be located.

In all of these undertakings, variations of the magnetic method had been employed, but in 1923 the process had practically been abandoned due to the unreliable nature of the results obtained. The seriousness of the situation is realized when it is learned that in that year more than 3,300 rails broke in track due to transverse fissures.

At about this time the writer was called in by the American Railway Engineering Association to perfect the electric method of inspection. The problem was to develop and build an inspection car that would travel over the tracks, making an ink record of the condition of the interior of every rail as regards cracks, seams, fissures, etc.

A call was sent out for pieces of rail that had broken in service, in the hope that these pieces might contain other fissures. The first shipment consisted of three rails, two from one road and one from another, where the transverse fissures had grown until they became very large and the rails had broken in service in each instance. 2,000 amperes was passed through these rails, and it was immediately determined that one piece was entirely free from even minute hidden flaws. The second one had one very large flaw—transverse fissure—that had not come to the surface, and the third piece of rail, some 15 feet long, contained no less than 11 transverse fissures. The importance of these fissures was immediately ascertained and a blue print made, showing both their size and location in the rail. Then the Rail Committee was invited

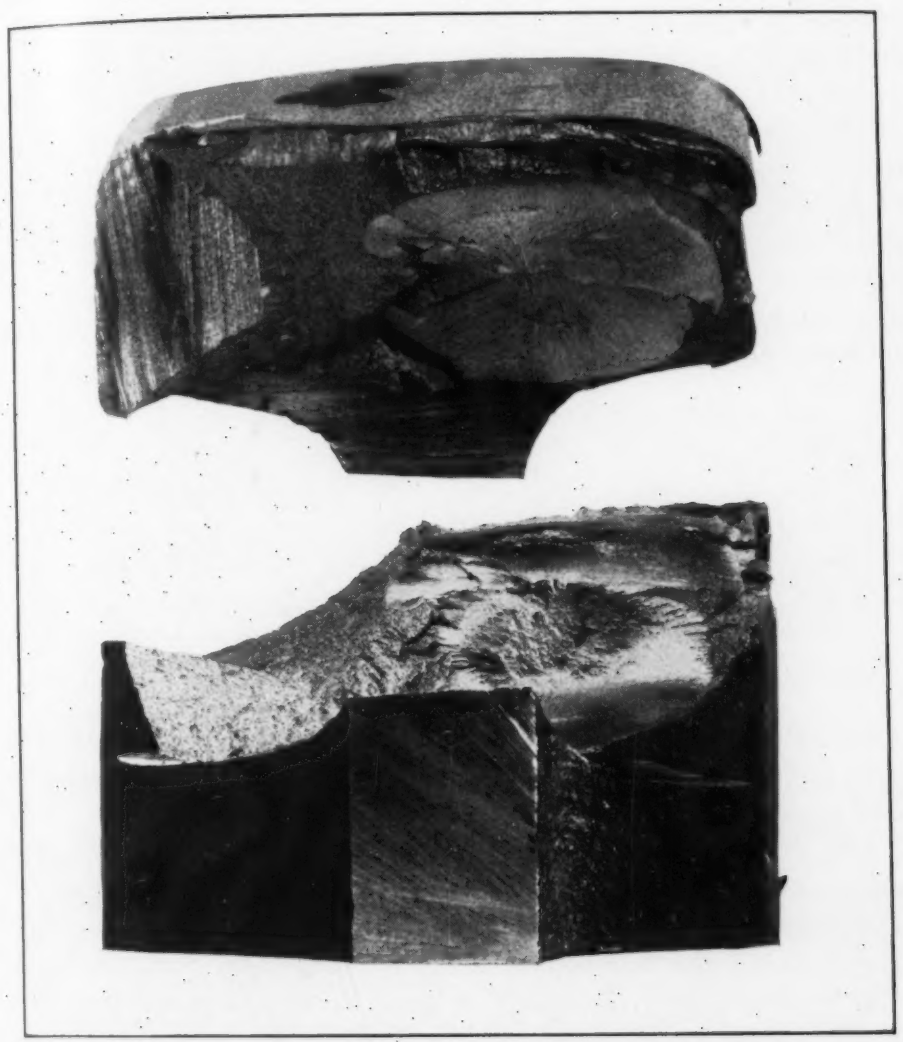

Fig. 3—Photograph Showing the First Transverse Fissure Ever to Have Been Apprehended by the Electrical Method.

to come to the laboratory, whereupon the rails were broken with 100 per cent results. Fig. 3 shows the first transverse fissure ever to have been apprehended by the electrical method, which may some day be of historic importance. Fig. 4 is a copy of the original tracing that was made of the third rail with exact location of the fissures, and Figs. 5 and 6 show photographs of the 11 fissures found in the rail, the smallest one at D, being only 1.37 per cent of the area of the head of the rail.

Following these tests some 80 rails, all of which had broken in service due to transverse fissures, were examined in the

laboratory and many fissures were accurately located. The railroad officials were convinced that when the apparatus indicated a fissure the fissure was sure to be there, but they felt that some proof was necessary that the apparatus was not missing any. To this end they selected three pieces of rail that appeared to them especially suspicious. The webs were burned off of these rails and the heads completely broken up into small pieces with a steam hammer.

The breaking was not shearing in any sense, and was of such a character that had there been any fissures they would have

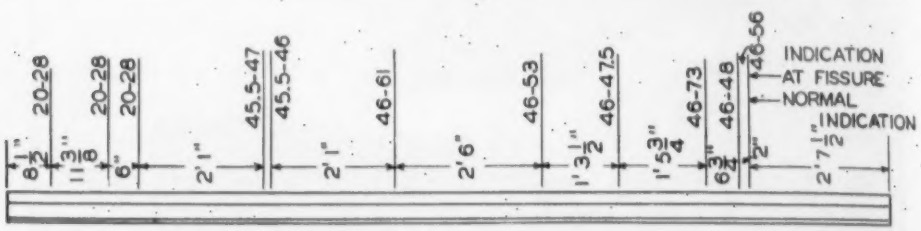

Fig. 4—Reproduction of the Original Tracing that was Made of the Third Rail with Exact Location of the Fissures. Eleven Fissures were Located in this Rail as Indicated.

located the break. Each fracture was examined carefully on both faces and the rails showed the finest possible steel structure with complete homogeneity.

In the course of this experimental work, light of more than usual interest was thrown on the reason why the magnetic method failed to differentiate between the various physical characteristics of the material itself and transverse fissures. This was because the transverse fissures could only operate the galvanometer through their functioning as air gaps, which were supposed to interrupt the flow of magnetic lines. The laws and mathematics governing the magnetic flux in air gaps have become perfectly understood and the reason why the air gap presented by a true transverse fissure gave no useful effect as an air gap is the fact that the element of length is practically completely wanting and non-existing. This has been proved through the following experiment:

With this method the location of the fissure can be made with a very high degree of precision—so much so that a drill point may actually enter the fissure, as shown in Fig. 7.

The reason for drilling was to introduce a fluid of the halogen group, which is possessed of extremely small molecules, expecting

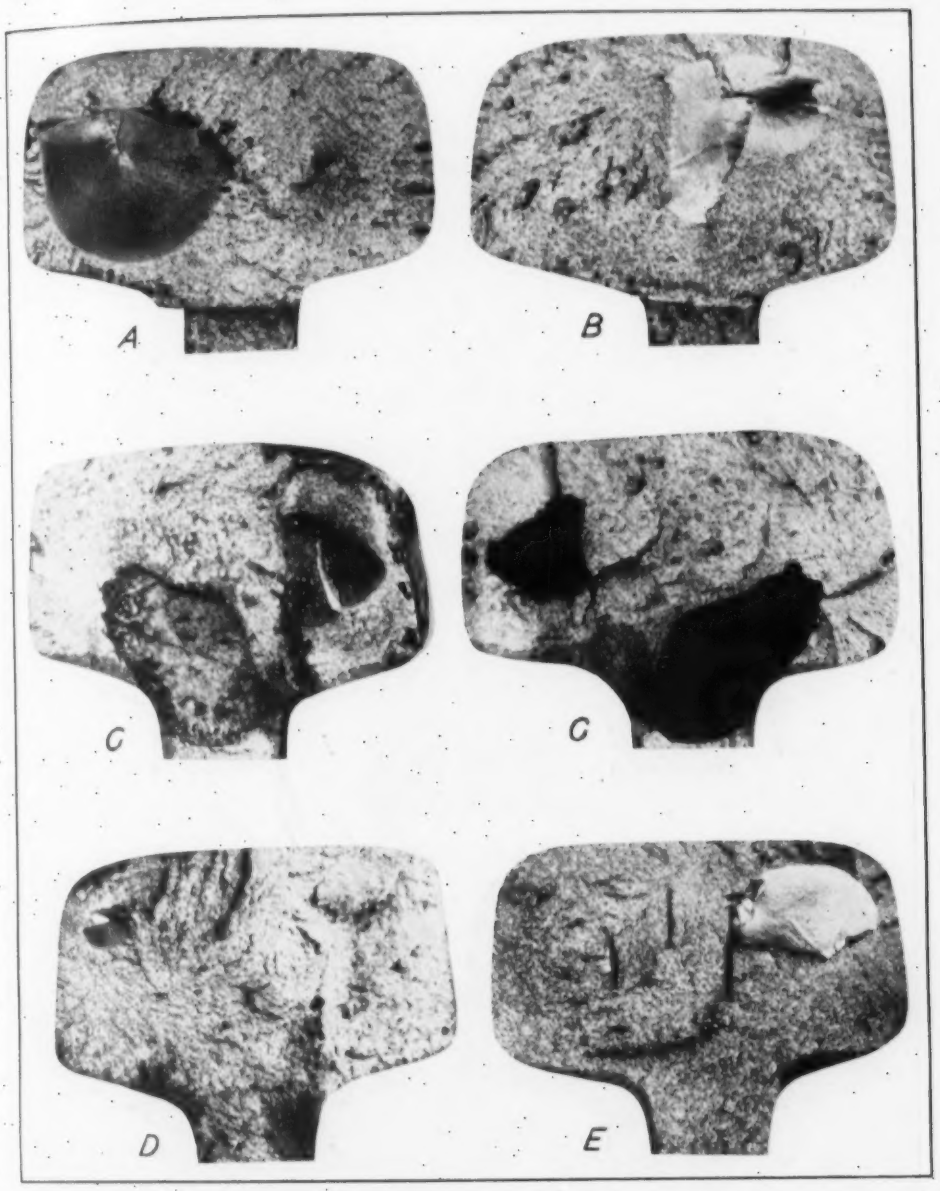

Fig. 5—Photograph of Fissures Found in the Rail.

this fluid to freely penetrate and discolor the two entire opposing faces of the fissure. The interesting fact was developed that after repeated applications of this fluid, even under some pressure head, the rail was broken at this point and not the slightest penetration could be observed, proving that the actual gap between the surfaces is sub-molecular in dimension and therefore sub-microscopic. The little spheres representing the small molecules of even a

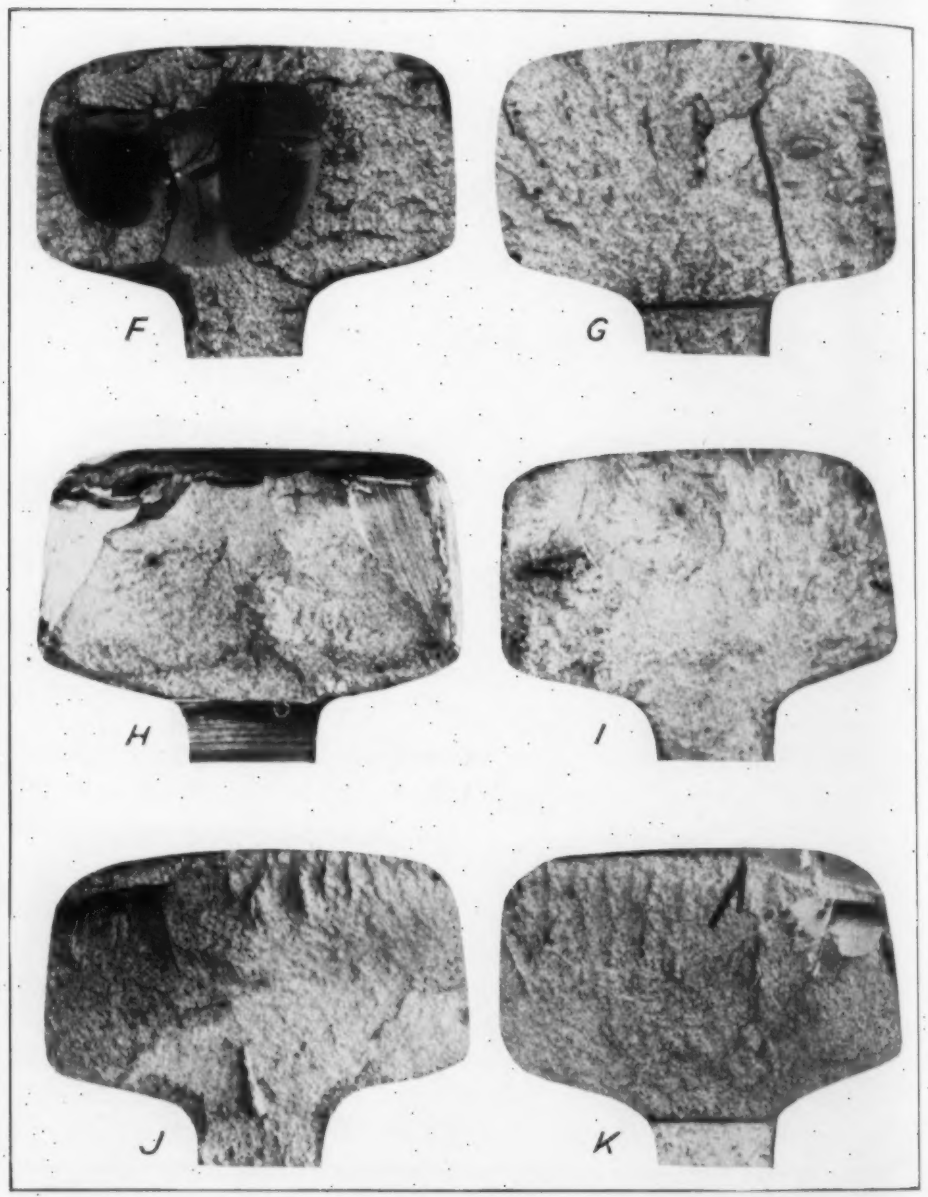

Fig. 6—Photograph of Fissures Found in the Rail.

halogen not only could not force their way into the crevice, but could not enter it to the slightest extent, leaving the surfaces bright, as shown in the figure. This is the first scientific proof of the extreme minuteness of the length of the gap longitudinally in the rail and the utter impossibility, therefore, of obtaining any

Fig. 7—Photograph Showing Drill Point Entering the Fissure.

interpretable disturbance in the magnetic flux passing through the rail due to a fissure.

The method having been proven practical and sound, a fissure detector car was constructed for the American Railway Engineering Association as illustrated in Fig. 8. It consisted of a standard track maintenance trailer car upon which was built an enclosure containing the power plant, radio apparatus and recording mechanism. A motor car was required for towing purposes as the detector car was not equipped for self-propulsion. The operating speed was 5 miles per hour or more.

Fig. 9 shows the power plant placed on the forward end of the platform, and includes a 25-horsepower gasoline engine with necessary starter and auxiliaries, directly connected to a 4000-ampere, 2-volt generator operating at 900 revolutions per minute.

Fig. 1 illustrates the contact brushes that go on the top surface of the rail, and between which flows the energizing current.

Fig. 8—Photograph of the Fissure Detector Car Constructed for the American Railway Engineering Association.

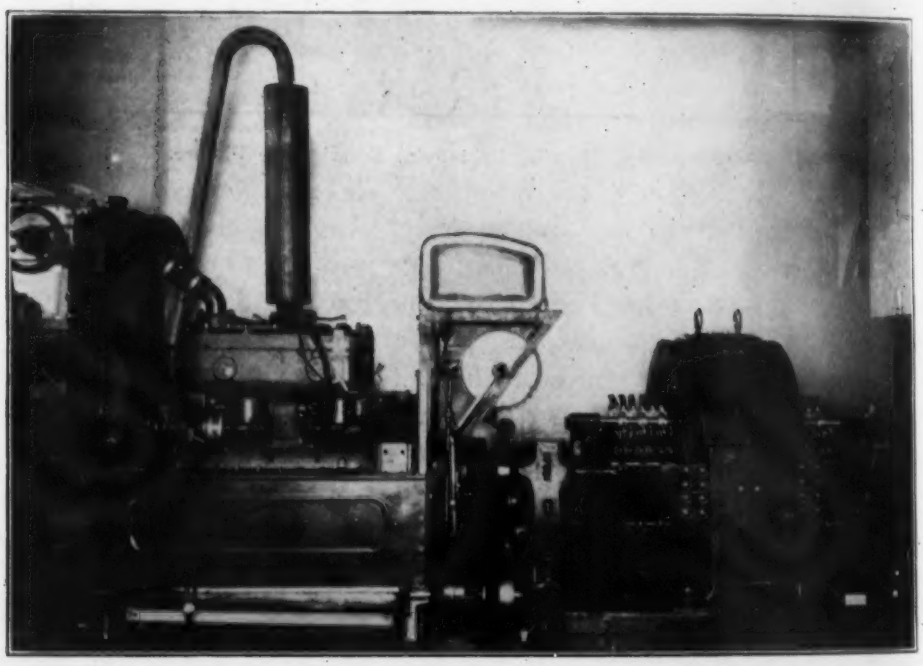

Fig. 9—Photograph of Power Plant for Detector Car Showing Gas Engine, Generator and Auxilliaries.

Each contact assembly consists of eight individual copper brushes pressed against the rail head by springs. These brushes are

mounted in a rigid frame which is raised and lowered by a lever in the car. There are two sets of eight brushes in contact with each line of rails.

Small potential brushes, or equivalent searching equipment, are shown mounted between the brushes and form the mechanism for picking up the difference in potential from the resistance effect of the air gap at the internal break in the rail head. This micro-voltage is carried to a set of four radio tubes which step it up two to three hundred thousand times.

Near the center of Fig. 1 the paint spraying device can be

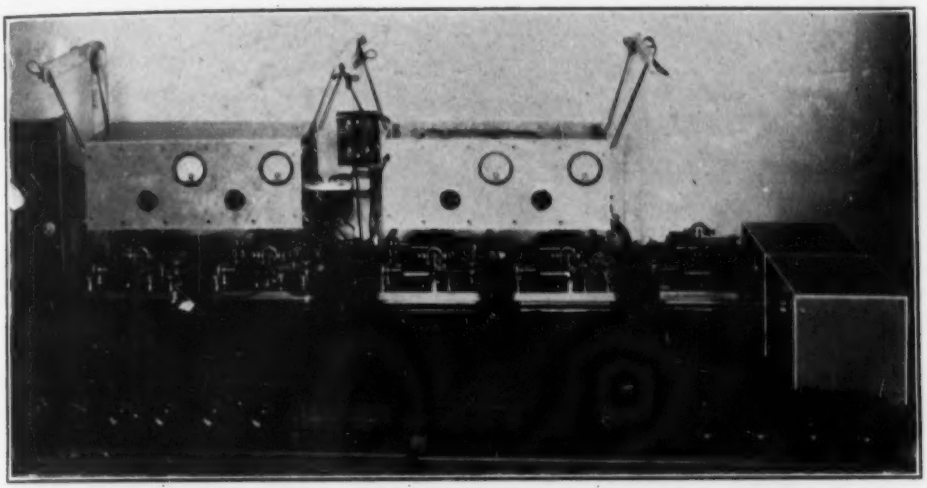

Fig. 10—Photograph of Table Containing Batteries, Amplifiers and Relays.

seen. A relay controls the release of a spray of paint against the side of the rail whenever a defect is found at any point in the length of the rail.

Fig. 10 shows the table containing the necessary batteries for the tubes. Above the table is shown the suspended aluminum case containing the amplifiers. On top of the tables are the relays, ten being required for various purposes.

Fig. 11 shows the recording table, on top of which travels a friction-driven strip of paper. Directly in contact with the paper are seven pens which are actuated by the relays in circuit with the tubes. Fissures located in one line of rails are indicated on the paper by three pens, and a similar set of pens for the opposite line of rails. The center pen records the location of joints. The relays are so adjusted that a short transverse line is drawn by one pen

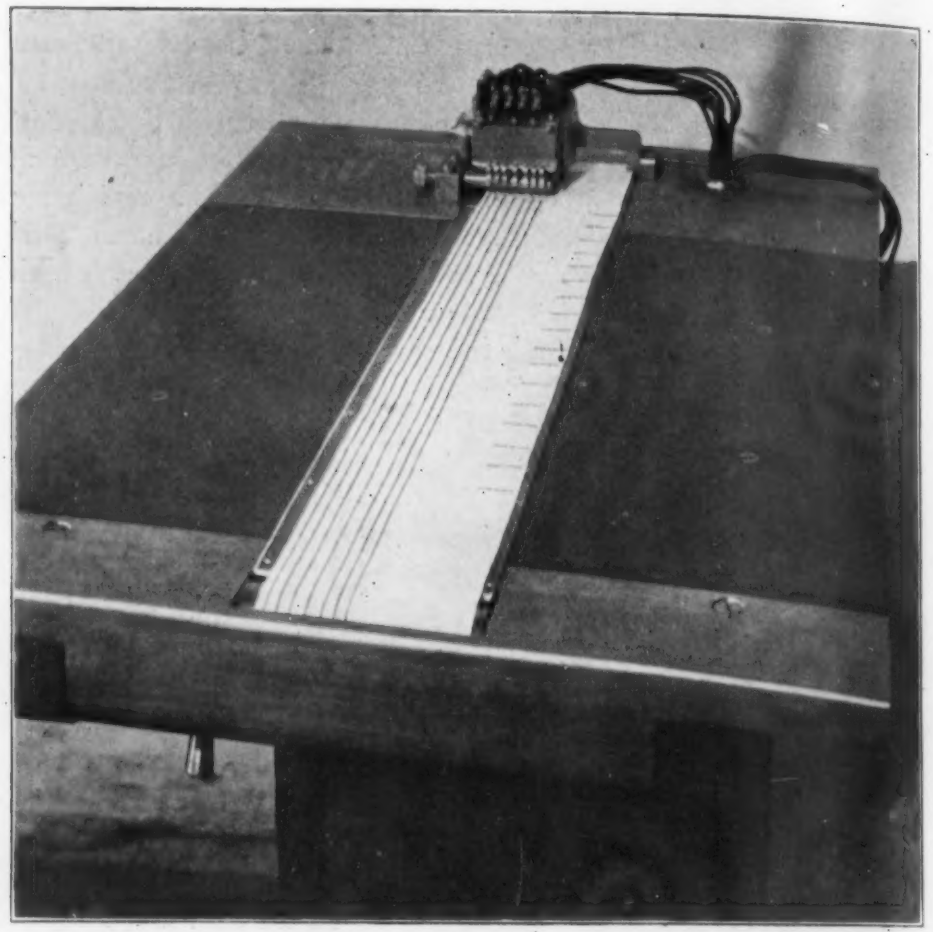

Fig. 11—Photograph of the Recording Table.

if the internal break is of small area, two pens operate if the break is of intermediate size, and all three pens if of large area. The fissure pens are automatically thrown out of circuit when the pen for location of joints operates.

The three lines to the left record defects in the left hand rail; the middle line locates the joints; the three right hand lines indicate defects in the right hand line of rails. The short transverse lines thus permanently record the location of internal breaks and their size.

With the completion of the fissure detector car for the American Railway Engineering Association, a second car (Fig. 12) was immediately built and placed in service on the railroads of this country. These two cars have now made accurate per-

manent records of some 800,000 rails in main line track, showing the exact condition of the internal structure of these rails. Hundreds of transverse fissures have been accurately located and the rails removed from track.

Although the detection of transverse fissures was the primary object of the cars, it immediately developed that they were locat-

Fig. 12—Photograph of the Second Fissure Detector Car.

ing compound and horizontal fissures, piped rails, split heads, and various other discontinuities in the rail head.

Previous to the advent of these cars there had been much speculation as to the probable percentage of internal transverse fissures per mile. It now develops from data obtained with the cars that the number of fissures per mile varies widely, the minimum figure being about 0.02 per mile and the maximum 3.1 per mile.

Now that fissures can be located and their size accurately determined, the rate of growth and factors governing that growth may be carefully studied. Experience thus far seems to indicate that after a fissure has started its growth is very rapid.

Other Applications

In the laboratory it was found possible to so increase the sensitivity and responsiveness of the detection method as to get

an accurate record of the soundness of a rail down to a flaw or defect representing less than 1/10 of 1 per cent of the area of the head of the rail. It is an important fact that this is found equally true with nonferrous metals. A complete set of apparatus was devised and taken to one of the largest rail mills and there set up and employed in investigating three thousand 39-foot rails varying from 90 to 130-pound sections. These rails had passed a most rigid inspection before being submitted to the process.

Rail after rail was passed through the process, showing a perfectly straight line on the record and complete soundness of structure. The entire batch of rails was remarkably free from defects, but such defects as existed were invariably picked up and recorded by the process both as to magnitude and exact position in the rail. A great many of these proved to be surface abrasions and defects that were not looked upon by the inspectors as objectionable, but the interesting feature is that all were located and recorded. Many "roll-ins" and head seams or surface cracks were found which had escaped the inspectors' observation, but were invariably located and recorded by the process and thus only brought under the observation of the inspector. Although the rails had been handled repeatedly by the magnetic type of lifter, and, although this had been greatly accentuated in some rails to ascertain the result, it was found that the accuracy of the inspection was not affected in the slightest thereby. It was found that heat treated rails could be searched as well as the normal rails. A high manganese rail that had been heat treated and was nonmagnetic was also brought to see if the process would work on it, which it proved to do with a high degree of accuracy.

A new rail from another mill broke while bending to lay in track on a curve, and by laboratory etching shatter zones were plainly shown. The next rail to this in the rolling had already been put into track, but was immediately found and lifted. A laboratory sample taken from one end showed the identical condition as to shatter cracks, so the remainder of this rail was sent some 500 miles by a member of the Rail Committee of the American Railway Association to be searched by the refined process going forward at the mill. We not only learned much from the examination of this rail, but were enabled to use it to check the accuracy of calibration as to magnitudes of our indications and records.

This rail immediately gave 28 indications of hidden internal faults on the record, which on a number of repetitions were perfectly consistent and accurately located. Portions about a foot long were sawed out which contained the largest indications, were taken to the laboratory, and by careful grinding and deep etching, photographs were obtained confirming each of the findings.

To give some idea of the capacity of this process for locating minute faults, two of these etched sections are illustrated in Fig. 13, giving a good idea of the extreme smallness of the imperfections found and recorded.

It has been noted that rails developing fissures after being only a short time in service are in the majority of instances found associated with shatter zones. Now that these zones can be so completely located and recorded by the nondestructive method, it is felt it might be wise to eliminate rails containing such defects from main track, especially where the traffic is dense, and utilize them in less important positions.

This method of inspection lends itself readily to the examination of bar and tubular stock of practically any size or composition, easily indicating pipes, inclusions, cracks, etc., that may be present in the various bars. A wide variety of stock such as standard bridge wire, both cold drawn and heat treated, alloy steel bars, and steel tubing up to 3.5 inches inside diameter and 4.5 inches outside diameter have been successfully inspected by the method. This class of stock may be tested at a speed of from six to eight feet per second.

The testing of car axles differs somewhat from the standard bar stock application in that their cross section is not uniform.

The failure of car axles in service is due in the majority of cases to fatigue failure which develops as a crack encircling the axle. The following is the method of inspecting axles that has been used for the past few years. The axle is first painted with kerosene oil and lamp black. This mixture is allowed to soak in for a few minutes and is then wiped off and replaced by a coating of whiting and alcohol. When this drys, the end of the axle is struck with a sledge, and any oil and lamp black that may have penetrated a crack is driven out, giving a black mark on the coat of whiting. Obviously this method can only hope to locate cracks

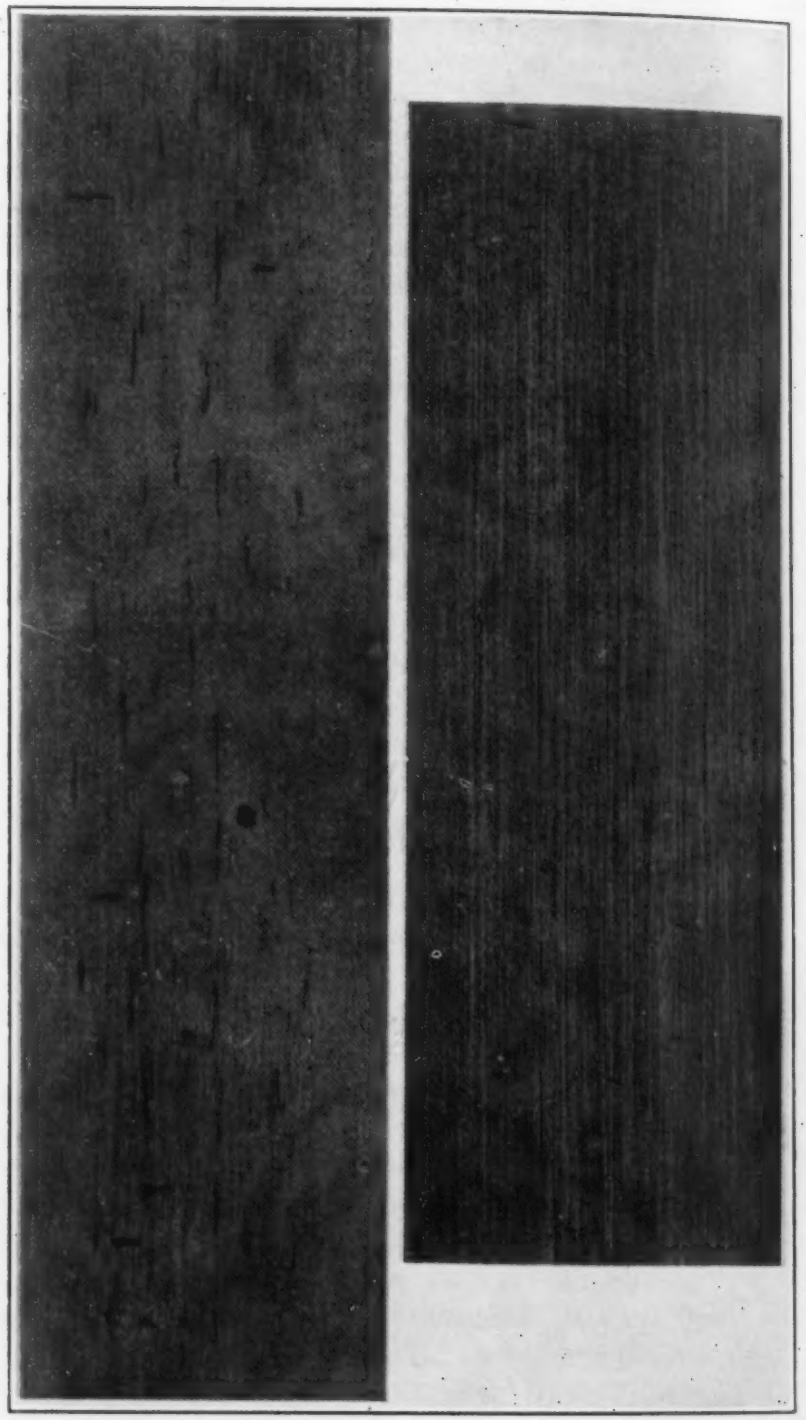

Fig. 13—Photograph of Etched Rail Section Showing Extreme Smallness of Recorded Imperfections.

after they have reached a size where the oil can penetrate below the surface.

The Sperry method of inspection applied to axles in rapid transit service has located and made a permanent record of these fatigue failures in the early stage, while they were still too small to be located by the method described above. When located in the early stage their growth may be arrested by turning down the axle a slight amount until the crack disappears. Longitudinal cracks were also easily located in similar axles, the total time for complete inspection being only a fraction of the time required by the old method.

The electrical method of inspection is not limited to the examination of uniform cross sections, but on the contrary may be applied to a wide variety of nonuniform pieces. Cast steel gear blanks have been successfully inspected by this method in spite of webs, bosses, and bolt holes, a special arrangement of the pick-up device being practically the only change from the standard equipment.

The inspection of boiler plate presents problems that are not present in any of the examples cited. In the rolling of plate stock, gas pockets or inclusions are sometimes rolled out into thin laminations or separations. If plate containing one of these laminations is used in the fire box of a locomotive a blister develops where the flaw occurs, due to the interruption of the heat gradient. An adaptation of the electric method has been developed which makes possible a rapid and thorough inspection of plates, insuring a product free from any flaw or lamination.

The welding field is at present seriously handicapped by the lack of a dependable method of internal inspection. Application of the electrical method to this problem has resulted in some very gratifying results.

Conclusion

The Sperry method of nondestructive inspection is now being employed daily on the railroads of the country to sweep the rails clear of the internal transverse fissure menace. This initial use of the method having proved successful, its application to a multitude of other parts is progressing rapidly. With the continual simplification and improvement which invariably accompanies the development of a new instrument, it is not too much to expect

that this new method of inspection will in the near future be as fully understood and as easily handled by the shop inspection departments as are the various hardness tests of the present day.

DISCUSSION

Written Discussion: By R. L. Sanford, physicist, Bureau of Standards, Washington.

No word of this discussion is intended in any way as a disparagement of the achievement recorded in Dr. Sperry's paper. Dr. Sperry and his associates are entitled to a great deal of credit for carrying through to practical success a method abandoned by others as presenting too great difficulties. The results given in the paper speak for themselves.

It would appear, however, that an erroneous impression with regard to the scope and possibilities of magnetic analysis might be received which the author probably did not intend to convey, and I would like to call attention to the following points:

(1) Nondestructive testing has a much wider scope than the detection of flaws and imperfections in the material. Not only is it important to be assured that each piece is sound and free from flaws but also that it has responded properly to treatment, either thermal or mechanical, so that it has the requisite structure and mechanical properties. It is in the latter field that magnetic analysis continues to hold its place as being the most promising of nondestructive methods in spite of the practical difficulties that are yet to be overcome.

(2) In his references to magnetic analysis, Dr. Sperry has fallen into the common error of giving isolated quotations without due regard to the context, Neither of the statements quoted was originally made with reference to the detection of flaws. In particular, the second quotation from my paper on magnetic analysis had reference to the correlation of magnetic properties with heat treatment alone in an attempt to establish fundamental relationships. This caution should be borne in mind because magnetic properties are functions of the structure actually attained and not necessarily of the nominal heat treatment.

(3) In mentioning the two methods of picking up indications of flaws, Dr. Sperry did not describe the means which have been found for detecting a deviation in the direction of the electric current in a rail. Since these means involve no actual physical contact with the rail, however, it seems reasonable to assume that the indication is obtained inductively from a change in direction or magnitude of the magnetic field associated with the test current. The test current circularly magnetizes the rail and it would appear that this method might have some of the uncertainty found in the straight magnetic method of exploration, though probably not to the same extent. I should expect that magnetic irregularities not necessarily associated with actual flaws might at times tend to confuse the record and so render the interpretation somewhat diffi-

cult. Perhaps the effect is small enough to be negligible or means have been discovered for neutralizing or accounting for it in the records.

Dr. Sperry has given the impression that the job was relatively simple and easy of accomplishment, but any one who has attempted similar developments well knows that many details had to be worked out and difficulties overcome in producing a practical device and so all the more credit is due for the final accomplishment.

Written Discussion: By W. C. Barnes, engineer of tests of the Rail Committee of the American Railway Engineering Association, Chicago.

I appreciate the opportunity of saying a word in praise of the very valuable method of nondestructive testing of metals developed by Dr. Sperry. It is a method that has already found practical application in the testing of rails in railroad track and further refinements will doubtless make it practicable for testing in other fields.

The writer has been in close touch with this development since its beginning, having in a way been responsible for its financing, as it was on his report and recommendation as engineer of tests of the Rail Committee of the American Railway Engineering Association that the necessary funds for development were secured from the American Railway Association.

The first fissure detector car constructed became the property of the American Railway Association and has, since passing its acceptance tests in the fall of 1928, been operated continuously under the direct supervision of the writer in the actual testing of rail in track.

During the first eight months' operation, in which eighteen hundred track miles of rail were tested on seventeen railroads, one hundred and forty-five transverse and compound internal fissures were located, in addition to many split heads, piped rails, broken bases, split webs, horizontal fissures, etc.

For the information of those not in close touch with the type of rail failure called the transverse fissure, I would explain that it is a fatigue failure starting at a nucleus within and approximately at the center of the cross section of the head of the rail. This nucleus is generally extremely small, being of the order of $\frac{1}{32}$ to $\frac{1}{8}$ inch diameter, although some are found having a diameter up to $\frac{5}{8}$ inch. Our rail committee, from its study of approximately thirty thousand transverse fissure failures which have been reported to it to date from railroads in the United States and Canada, believes that there is unanswerable evidence that the nuclei or initial defects in the rail head which later develop into transverse fissures under service stresses, exist in the rails when received from the mills.

The fissure grows outwardly from the nucleus in a transverse plane at a rate determined by service conditions. Fissures have been known to cause rail failure within six weeks from the date of the laying of the new rail and in other rails to cause failure after fifteen years of service.

The nucleus, or initial defect in the rail, when delivered from the mill, is generally so very small that only an extremely sensitive form of the

Sperry method could be successful in locating it. This extreme sensitiveness naturally magnifies the effects of minor surface imperfections and renders identification difficult. It is greatly to be hoped that Dr. Sperry will succeed in making his method practicable for use in the mill on new rail.

I wish to give all credit to Dr. Sperry for his wonderful device which, I believe, will be found very useful in nondestructive testing in many fields, but I do not want my railroad friends to misunderstand Dr. Sperry's conclusion as printed on the bottom of page 789 that "the Sperry method of nondestructive inspection is now being employed daily on the railroads of the country to sweep the rails clear of the internal transverse fissure menace." This statement is a little too sweeping.

Our experience proves that many fissures can and are being removed from track as a result of the use of the Sperry method. We are probably removing all that are of a size that are immediately dangerous, but it is not yet possible to detect and recognize minute fissures which will sooner or later develop into menaces.

The track is like your lawn; you can weed out the dandelions of appreciable size, if you work hard enough, but a new crop will surely appear from the seed already in the ground.

Written Discussion: By Hunter MacDonald, chief engineer, Nashville, Chattanooga and St. Louis railway, Nashville, Tenn.

Dr. Sperry's paper clearly indicates that nondestructive testing of manufactured metal is not a mere dream but the field to which he has already applied it is somewhat limited so far as the classes of articles tested are concerned. It is to be expected that the ability to test steel castings and forgings of locomotives and cars which present variable shapes will eventually be worked out. The laboratory and mill tests on rails have proved the possibility of locating shatter zones in advance of placing the rails in service. It would seem that if the shatter zones can be eliminated in advance, the transverse fissure problem might be greatly simplified in rails laid in the future, but it seems yet to be determined whether there are not nuclei which may develop into transverse fissures elsewhere than in conjunction with shatter zones and whether these nuclei are susceptible of advance detection.

The fact that fully developed fissures have occurred in rails tested by the car only a few days previous and no indication of these fissures appeared on the tape, clearly points to the necessity of intensive study of the rapidity of development of such fissures.

Driver burns on the head of the rail have proved to be a troublesome question in the operation of the detector car and I understand the present practice is for an observer on the car to endeavor to identify those passed over by the car and mark their indications on the tape in order that they may be left out of consideration. Such a practice might lead to omission of fissures which might exist under these burns and possibly cracks in the surface of the head due to thermal hardness resulting from the slipping of the wheels.

The following is the concluding paragraph of the report of Jan. 14, 1921, by the Bureau of Safety, Interstate Commerce Commission, covering investigation of an accident on the B. and O. railroad at Glenwood, W. Va., Dec. 11, 1919:

"The prevention of wheel burning in its entirety presents great practical difficulties. Efforts should be directed toward minimizing these destructive influences. The presence of incipient cracks as they were displayed by this rail is evidence of impaired strength and constitutes a warning signal that a dangerous state has been reached."

Oral Discussion

E. W. CARUTHER: Unfortunately, I have had very little opportunity to prepare any comment on the subject of the paper. My only attempt in commenting will be from the standpoint of the study and inspection of rails. In commenting on Dr. Sperry's enlightening and instructive paper I would like to preface a few brief remarks with the statement that I was most fortunate in having the opportunity of being on the Sperry transverse fissure detector car during the entire 6-day period it was operated on the Pennsylvania Railroad. I would also like to state that the operator was most painstaking and efficient in handling the car and no effort was spared to produce the most accurate results obtainable. During this 6-day period a total of over 14,000 rails were tested. Of the above rails 21 were removed from the track on account of indications by the detector car of interior defects of various natures.

The results of the laboratory investigation of the above 21 rails showed first about 50 per cent of the indications by the Sperry detector car of internal defects failed to show interior defects by the drop test, and second, internal defects were found in the rails by the drop test which were not detected by the Sperry detector car.

Without any intention whatever of taking a pessimistical view of the subject; Dr. Sperry's statement to the effect that the method of nondestructive testing described in the paper "is sweeping the tracks clear of the menace of internal transverse fissures" we think is rather extravagant. While this method is unquestionably promising and encouraging, the cold facts taken from the records of operation of the detector car are such that in its present state of development it surely cannot be classed as entirely successful. If we grant, as Dr. Sperry states, that "experience thus far seems to indicate that after a fissure has started, its growth is very rapid," to sweep the tracks clear of the menace would mean repeated inspections at frequent intervals. While the term "rapid" is not defined, on a basis of an interval between inspections of say 30 days, it would require no less than 40 detector cars operating continuously, except Sundays and holidays, to cover a railroad system with 15,000 miles of main track. Granting 100 per cent operating perfection and efficiency of the car, which cannot be at present conceded, as transverse fissures were found in rails tested by the car that were not indicated on the tape, with our present knowledge of the rate of development of transverse fissures it is very doubtful if a 30-day interval would, without question, sweep the tracks clear of the menace.

It is not with any intention of detracting from the value of the use of

the car that I have taken the opportunity of making these remarks. It is simply that the apparatus, as it is now being used, while very valuable, is certainly far from perfection. There are entirely too many circumstances that give, I might say erroneous, or false indications and at present, while the car is certainly valuable, from a standpoint of investigation we cannot feel that it is a cure-all for the menace of transverse fissures.

CHAIRMAN H. W. GILLETT: As I understand it, your experience has been that in the laboratory the sensitiveness and accuracy was practically up to what Dr. Sperry described, but that when car was put on the track the difficulties were so great that this state of perfection in the apparatus was diminished.

E. W. CARUTHER: That is exactly the situation, and if I may have a few more minutes, I will explain a little further. The car in operation is dependent on some variable factors. In the first place it is necessary to obtain good confact with the rail in order to deliver or saturate a short section of the rail with a uniform flow of current. That, we all know, is not altogether practical in carrying a motion contact. A slight interference or defect in the surface of the rail very materially affects the current that is injected into this section of the rail. Many feet of the rail that are passed over, if not in perfect condition, do not receive a uniform saturation of current, this causes fluctuations that more or less make the records questionable. In order to fully check conditions of that kind, in the operation on the Pennsylvania Railroad, we conducted the work in several different ways, that is, under several methods. One was to start on one day making as much mileage with the car as we practically could. The operating department gave us the full use of the track, which was exceptional and would be out of the question under normal operation to expect anything of the kind over a very dense traffic section of railroad, which, of course, is the very portion of the railroad that is most susceptible to the perils of the transverse fissure. Under this method we were able to make about 15 miles a day. I think one day we averaged a little over, and another day a little under. In making such a day's run the tape record was very carefully followed, and when an indication was shown on the tape, the car was stopped and a very careful hand check was made of the section of the rail in which was indicated some internal defect.

The method detection on the hand check was somewhat different from the operating method. The operating method of detection is by a runner carried a small distance above the surface of the rail, and as I understand it, (I am not an electrician), and Mr. Drake will probably give you a better idea of it when he replies, is based on the principles of magnetism. The lines of force which surround the rail through which the current is passing are cut by the element in the runner thus inducing a feeble current flow through the circuit in which the runner element is connected. With this method variations in contact as well as variations in cross section of the rail cause fluctuations in the induced current and corresponding records on the recording tape. The hand check is practically a positive method. The rail is thoroughly cleaned and a contact runner is passed over the rail. Any variation in the capacity of the conductor to carry a current is indicated on a galvanometer connected in the circuit with the contact

runner. In order to check the record of the car, whenever an indication was shown on the tape, the car was stopped and the hand check made. In making a run under this method and hand checking indications, as I said before, we were able to make but about 15 miles a day.

The other method of operating was used on a few selected stretches of experimental rail of different kinds, that is, different steel analyses. In those cases the car was run without stopping, from one end of the stretch of rail to the other end. The test stretch in some cases consisted of 40 or 50 rails. The car was then backed up and a second and third running made straight through to the end of the stretch of special rails. The tapes were then compared and were not always found to be identical. You can see that a single running does not necessarily give you what we would hope to be the truth, because we had indications on some tapes that we did not have on others. The surface contact is greatly interfered with by a condition that is very prevalent on a railroad, that is, what is generally termed driver wheel burns. In almost every case a severe driver burn will give an indication on the tape on the car of equal magnitude to a very severe transverse fissure and I think that on practically all railroads you will find plenty of driver burns. My experience in talking with a number of other railroad men who have operated the detector car is to the effect that an observer has to stand on the rear of the car and when he passes a driver burn the word is passed on to the operator to the effect that a driver burn caused a certain indication on the tape. That is not necessarily a clean bill of health for that indication on the tape as a fissure may also be present. The only proper way would be to stop and check by hand, which would be almost an endless task. I do not know whether I have made myself reasonably clear or not. The point I would like to bring out is that while we are trying our best to work along with this development we regret to see statements made that are in our opinion more rosy and optimistic than we think should be made over so serious a problem as the transverse fissure.

ROBERT JOB: Dr. Sperry's constructive achievement in developing an apparatus for detection of defects in rails is so well known in railroad circles that comment as to the mechanism is unnecessary, and we understand that study is being given to adapt it to varying conditions met in service. Evidently there are two uses to which it can be put. First, the detection of defects already existing in track, and, secondly, the detection at the mill of the incipient defects from which transverse fissures grow.

On page 789, Dr. Sperry states that many of these nuclei can be detected and located. In this connection the report of Freeman and Solakiam in the Bureau of Standards Journal of Research, August, 1929, is of a very special interest, and in connection with one of the rails examined by Dr. Sperry for the Bureau (pages 237 and 238 of the Journal) it is stated by Dr. Sperry there are no fissures of the size of one per cent of the area of the head or larger. A one per cent fissure is the smallest that we can locate with the facilities now at hand.

Subsequent examination of this rail showed presence of shatter cracks, so that evidently some of these defects, liable to result later on in serious difficulty are—as would be expected—smaller than one per cent of the area of the section.

It is our feeling, however, that at the present stage of Dr. Sperry's development the equipment might be used to great advantage in the mills in locating the precise points in the manufacture at which shatter cracks and similar defects are formed, whether in the ingots themselves or during the course of the rolling. It should then be possible to develop a remedy for this condition and to secure steel free from these defects.

It is our hope that this constructive work will be continued by the Bureau of Standards or other departments of the government and the logical place would seem to be in the mills.

Dr. Sperry is to be congratulated for the important development which he has effected.

W. A. HAENDIGES: Several years ago a paper was read before the Buffalo Chapter of the American Society for Steel Treating on "Transverse Fissures."

The author of the paper advanced the theory that chemical composition has something to do about its cause and prevention. He stated that instead of a high carbon (0.90 per cent), low manganese (0.60 per cent) steel, a high manganese (1.5 per cent), low carbon (0.60 per cent) steel would be much better. He also stated that since this specification had been in use, very few cases of transverse fissures had been reported.

E. F. KENNEY: Mr. Chairman, will you ask Mr. Drake to tell us about the rails which he has investigated at one of the mills.

H. C. DRAKE: We have tested 3,000 rails approximately at the mill. The rails were free from any internal cracks. Any cracks that were present such as head seams, roll-ins, etc., although they were invariably hidden by mill scale, were located.

The test run of the fissure detector car on the Pennsylvania Railroad took place last year just five weeks after the car had started testing.

Mr. Caruthers in his entire discussion has been talking of that fissure car as it was at that time. When he speaks of the detector car "in its present state of development" and "as it is now being used" he is still referring to that original car before any alterations or improvements had been made.

Dr. Sperry's paper has dealt with the modern fissure detector car.

No one expected the first detector car in its original form to be the last word in fissure detection, but it found fissures and was felt to be a big step in the right direction.

Instead of criticising the car as it was initially, let us examine into its record some months later.

Five months after the car was accepted the following report was given at the American Railway Engineering Association's Convention in March, 1929, by W. C. Barnes, engineer of tests for the Rail Committee.

"The car is being improved from week to week, additional apparatus and equipment is being put on which is improving the speed of detection and the accuracy of detection and the records now made are not at all comparable with those made in the beginning.

"On one road 18 rails in which fissures were detected were removed and immediately broken for verification and in each case a fissure was disclosed.

"With regard to accuracy, I should mention that we had a retest made on

a certain road for 85 miles, going over the same track that was tested previously, and in all that 85 miles every flaw detected on the retest appeared on the original record with the exception of one. I think that is an extremely good record."

These are statements by the engineer under whose supervision the American Railway Association's car has been operating since its acceptance.

You have also heard Mr. Barnes' discussion read today in which he states that the car not only finds the transverse fissures but also split heads, piped rails, broken bases, split webs, horizontal fissures, etc.

The total rail failures reported due to transverse fissures for the year 1927 were 4,742. In the 17 years preceding the advent of the Sperry detector car not one internal transverse fissure had been located in track by any method.

In the first year of fissure car operation more than 600 transverse fissures had been detected, verified and removed from track. Think of it, in the first year of car operation the fissures detected equalled one-eighth of the total reported for 1927.

The above facts should be very encouraging to those interested in the prevention of transverse fissure failures in track.

With regard to the application of this method at the rail mill, we do not know from our tests whether shrinkage cracks are in new rails or not as we have tested but 3,000 rails.

The apparatus at the steel mill had an opportunity of testing a rail from another mill. When we tested that rail we obtained 28 definite indications. At the three larger indications the rail was cut deep etched and the cracks were right there. That will give you an indication of the sensitivity of the outfit.

The discussion by Mr. Hunter MacDonald is very welcome, coming as it does from one who has kept in touch with the progress of the fissure detector car.

Driver burns on the head of the rail represent a reduction in cross-section at that point. If the reduction in area is equivalent to that produced by a fissure then the burns will be recorded and painted by the detector car. Recent improvements in the hand test equipment have reduced the time required to check a burn for transverse fissures to 1½ minutes. This time interval is so short that all questionable burns may now be checked without great loss of time.

As Mr. MacDonald has said, the intensive study of the growth of transverse fissures is very necessary. With the detector car growth of the fissure may be followed closely and the relation of the various factors governing that growth such as tonnage, speed and road-bed, etc., may be readily determined. The electrical method of detection may play a similar role in the testing laboratories.

Specimens undergoing fatigue tests may be examined frequently and a complete history may be obtained of the progress of any minute cracks.

Author's Closure

We appreciate very much the criticism of so high an authority on the work that we have been prosecuting during the last six years.

Regarding the magnetic process, no disparagement of this method

was intended. The difficulty in interpretation has been, and it seems is still, its greatest handicap. The electrical method, on the other hand, with the proper adjustment of energizing current, is very straightforward and very smiple and unerring as to interpretation.

With regard to the last point, we have found that if we have too weak current Mr. Sanford is correct, but the criticism is correct only when we use too weak currents. We have found that by increasing the current saturation the physical characteristics can be suppressed to a point where they show very little, if any, response on the record when we are after internal discontinuities. This statement at once reveals one very excellent feature regarding the electrical method, as by soft-pedaling the energizing current and bringing it into proper control, different kinds of internal irregularities can be brought onto the record. Some of these it is easy to interpret but others, in common with experience with the magnetic method, are very difficult of interpretation and have been found to be misleading.

I am under deep obligation to Mr. Barnes, who is a very busy man, for the trouble he has taken to give us such a very complete account of the operation of the first transverse fissure detector car. Great value attaches to his statement owing to the fact that it comes from first hand and intimate contact with all the operations of this car since its beginning.

The extension of this electrical testing method to a long list of other uses also tends to emphasize its becoming more completely established as time goes on.

THE ENGINEERING INDEX

Registered United States, Great Britain and Canada

In the preparation of the Engineering Index by the staff of the American Society of Mechanical Engineers some 1700 domestic and foreign technical publications received by the Engineering Societies Library (New York) are regularly searched for articles giving the results of the world's most recent engineering and scientific research, thought, and experience. From this wealth of material the A. S. S. T. is supplied with this selective index to those articles which deal particularly with steel treating and related subjects.

AIRPLANE ENGINES

MANUFACTURE. Nickel Cast Iron Engine Cylinders. E. J. Bothwell. *Aero Digest*, vol. 15, no. 1, July 1929, pp. 104-106, 5 figs.

Use of cast iron for aircraft-engine cylinders is discussed; function of nickel in bringing about desired improvements in cast iron is taken up; experience with a few engines using nickel cast iron cylinders is related, including Hurricane, Brownback, and Wright airplane engines.

MANUFACTURE. Quality Problems in Aircraft Engine Production, G. J. Mead. *Aviation Eng.*, vol. 2, no. 8, Aug. 1929, pp. 11-13 and 23, 5 figs.

Quality depends on proper design as well as selection, manufacture, and inspection of materials used in fabrication of power plant; quality standards; checking forgings; inspection operations; engine test runs; inspection costs; process inspection; government type tests.

AIRPLANE MANUFACTURE

Aircraft Production, H. C. Deckard. *Aviation Eng.*, vol. 2, no. 8, Aug. 1929, pp. 18-21, 11 figs.

Methods employed by Fairchild Airplane Manufacturing Corp. for producing cabin-type planes are described; plan of procedure in lining up product for production; use of graphic charts in scheduling work; production organization; jigs in wood work; production of aircraft at present time is not great enough to warrant fully progressive manufacturing methods.

HEAT TREATMENT. Heat-Treating Alloy Steel Airplane Parts, C. B. Phillips. *Machy. (N. Y.)*, vol. 35, no. 12, Aug. 1929, pp. 943-945, 2 figs.

Description of heat-treatment method employed by Fairchild Airplane Manufacturing Corp., Farmingdale, L. I., for construction of airplanes; chrome-molybdenum steel used for fuselage tubes and welding fittings; low-carbon steel employed for fittings brazed to parts; bolts and other small parts made from nickel steel; chrome-nickel steel used for parts to be case hardened, forgings, and fittings; chrome-vanadium alloys used for crankshafts, connecting rods and other parts; layout of heat-treating department.

HEAT TREATMENT. Heat Treating Aircraft Parts, H. C. Kneer. *Iron Age*, vol. 124, no. 9, Aug. 29, 1929, pp. 519-524, 9 figs.

Application of heat treating to parts of airplanes; comparison of strength of steel and other materials; savings in weight and improvement in strength and safety resulting from heat treating.

AIRPLANE MATERIALS

ALUMINUM ALLOYS. Light Alloys, L. Aitchison. *Times Trade and Eng. Supp. (Lond.)*, vol. 24, no. 576, July 20, 1929, (Aero Sec.) p. 22.

Position which aluminum and its alloys can occupy in airplane construction is outlined; ratio of maximum stress of different metals to their specific gravity showing superiority of aluminum in some respects; uses of different alloys; heat treatment of forgings; ductility and strength.

ALUMINUM ALLOYS. Aluminum and Its Alloys in Aircraft, T. W. Bossert. *Am. Electrochem. Soc.—Advance Paper* no. 33, for mtg. Sept. 19-21, 1929, pp. 359-365.

Evolutionary stages of aircraft construction are outlined; widespread adoption of metal construction in aircraft has resulted from availability of strong aluminum alloys, with strength of structural steel but only one-third its weight; properties of these alloys are outlined and characteristic examples of their application are described and illustrated.

BERYLLIUM. The Possible Use of Beryllium in Aircraft Construction, H. W. Gillett. *Am. Electrochem. Soc.—Advance Paper*, no. 20, for mtg. Sept. 19-21, 1929, pp. 219-222.

Physical properties of beryllium are briefly reviewed; outstanding property is high modulus of elasticity, which is nearly three times that of magnesium; beryllium is more abundant in earth's crust than either lead or zinc; future development and application

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of metal are discussed at length, and it is concluded that beryllium will some day be important factor in aircraft construction.

MAGNESIUM ALLOYS. Magnesium and Its Alloys in Aircraft, W. G. Harvey. *Am. Electrochem. Soc.—Advance Paper*, no. 34, for mtg. Sept. 19-21, 1929, pp. 367-377, 6 figs.

Magnesium metal is one-third lighter than aluminum, and is used in airplane construction; due to its inherent chemical and mechanical characteristics, it has been difficult to work metal into useful shapes; however, recently, through discovery of methods of purification of metal and of methods of heat treatment of magnesium alloys, most fabricating obstacles have been overcome; mechanical properties of magnesium alloys are tabulated.

METALS. Metals Used in Airplane Making, G. S. Herrick. *Iron Age*, vol. 124, no. 4, July 25, 1929, pp. 211-214, 7 figs.

Description of various metals used in manufacturing airplanes; increasing volumes of chrome-molybdenum, nickel, and high-carbon steels and aluminum alloys employed; chrome-molybdenum steel most used; fuselage coverings; black sheet stampings; steel cord and tie rods for bracing; strength and resistance to corrosion most important factors in materials for airplane construction.

METALS. Light Alloys for Aircraft. *Iron Age*, vol. 124, no. 10, Sept. 5, 1929, pp. 615-616 and 646.

Review of Cleveland meeting of Society of Automotive Engineers and Aeronautical Chamber of Commerce of America with brief abstracts of papers; Aluminum and Magnesium, Being the Lightest Commercial Metals, Are the Most Suitable for Use in Aircraft Construction, E. H. Dix, Jr.; Modern Light Alloys and Their Application to Aircraft Engine Design, G. D. Welty; The New Metal Beryllium, C. B. Sawyer.

TUBING. Tubes and Their Uses, W. W. Hackett. *Times Trade and Eng. Supp. (Lond.)*, vol. 24, no. 576, July 20, 1929, (Aero. Sec.) p. 21.

Processes are outlined by which hollow bloom is brought to fine quality and light weight of finished tube for airplanes; 800 special sections of weldless steel tube; great future for stainless steel tube; heavy gage tubes for axles were lightened by being taper-turned on outside of tube.

ALLOY STEEL

STEEL PLANT EQUIPMENT. The Use of Alloy Steels in Iron and Steel-Mill Equipment, E. R. Johnson and O. Bamberger. *Am. Soc. of Mech. Engrs.—Advance paper*, for mtg. Sept. 11-13, 1929, 5 pp.

Requirements of iron and steel-plant equipment which necessitated substitution of various alloy steels for plain carbon steels; substitution of alloy steels in Central Alloy Steel Co.'s mill for general equipment; alloy steels used for different parts of steel mill and sheet-mill equipment and heat treatment given each are described; all shafting being replaced with chrome-nickel steel.

TEMPERATURE EFFECTS. Effect of Alloying Elements Upon the Stability of Steel at Elevated Temperatures, A. E. White and C. L. Clark. *Fuels and Steam Power (A. S. M. E. Trans.)*, vol. 51, no. 12, May-Aug. 1929, pp. 213-227 and (discussion) 227-228, 90 figs. partly on supp. sheets.

Stability characteristics are enumerated; methods of investigation are outlined and results of tests are expressed in various curves and tables; six full pages of half-tone prints showing photomicrographs of alloy steels.

ALLOY STEEL PROPERTIES

Welding Facts and Figures, D. Richardson and E. W. Birch. *Welding Jl. (Lond.)*, vol. 26, nos. 309 and 310, June and July 1929, pp. 173-175, 178 and 198-200.

June: Properties of duralumin and other aluminum alloys are given as aid to satisfactory welding. July: Copper alloys are classified and variety of uses indicated; precautions to be followed in successful welding of commercial copper.

ALLOYS

New Developments in Metals and Alloys, O. W. Ellis. *Can. Chem. and Met. (Toronto)*, vol. 13, no. 8, Aug. 1929, pp. 26-30, 4 figs.

Constitution of aluminum-copper alloys is analyzed; effect of heat treating alloys; recent developments in alloys of zinc and aluminum, aluminum and silicon; copper and silicon, copper and cadmium and various nickel alloys.

PROPERTIES. Electric Conductivity, Thermal Stretch and Hardness of Magnesium Zinc Alloys (Die Elektrische Leitfaehigkeit, die Thermische Ausdehnung und die Haerte der Magnesium-Zink-Legierungen), G. Grube and A. Burkhardt. *Zeit. fuer Elektrochemie (Berlin)*, vol. 35, no. 6, June 1929, pp. 315-332, 11 figs.

Theoretical analysis of test, testing equipment and results.

X-RAY ANALYSIS. X-Ray Studies On Alloys, A. F. Westgren and G. Phragmen. *Faraday Soc.—Trans.*, vol. 25, no. 98, July 1929, pp. 379-385, 3 figs.

Brief review of accumulated data for purpose of discovering whether any regularities can be traced governing phenomena in this field of research; connection between type of structure and qualities of atoms in intermetallic phases is dealt with; short account is given of change of average volume of atoms in alloys with varying composition.

X-RAY ANALYSIS. The X-Ray Investigation of Alloys: A Summary of Published Information 1921-1928, C. F. Elam. *Inst. of Metals—Jl. (Lond.)*, vol. 41, no. 1, 1929, pp. 329-342.

Summary of results obtained in applying X-ray analysis to study of metal crystals in table form showing metals arranged alphabetically with method used, composition and structure given. Bibliography.

ALUMINUM ALLOY CASTINGS

HEAT TREATMENT. Regulated Control in Heat-Treating Aluminum-Alloy Castings. *Am. Mach.*, vol. 71, no. 10, Sept. 5, 1929, p. 403, 2 figs.

Method used by Aluminum Company of

America to heat-treat and test castings of aluminum alloys under nearly automatic conditions is illustrated.

ALUMINUM ALLOYS

Solution Potentials of Aluminum Alloys in Relation to Corrosion. J. D. Edwards and C. S. Taylor. *Am. Electrochem. Soc.—Advance Paper*, no. 32, for mtg. Sept. 1929, pp. 351-358.

Potential differences arising from contacts between aluminum and aluminum alloys, as well as other metals, in presence of electrolyte, are of theoretical interest and practical importance; although these potential measurements show such wide variations that their quantitative significance is limited, qualitatively they are important in explaining behavior of metals in contact under corrosive conditions.

Aluminum, die Leichtmetalle und ihre Legierungen, P. Molchior; im Auftrage der Deutschen Gesellschaft fuer Metallkunde. Berlin, V. D. I. Verlag, 1929, 280 pp., illus., tables, diagrs., 15.-r.m.

Handbook on aluminum and magnesium and their alloys, which aims particularly to meet practical needs of engineers; metallography, chemistry and physical properties of metals are described; methods of shaping, finishing and joining are explained; uses of metals and alloys for various purposes are related; standards of various countries are given; much scattered scientific information is made conveniently accessible to machine builders. Eng. Soc. Lib., N. Y.

Some Alloys of Aluminum, G. M. Dyson. *Chem. Age, (Lond.)*, vol. 21, no. 523; July 6, 1929, pp. 1-2, 1 fig.

Aluminum is manufactured to extent of 220,000 metric tons per year, much of which is used not as metal itself, but in form of various alloys, use of which becomes necessary in order to overcome various defects which arise from use of aluminum alone; nickel in aluminum bronzes; aluminum-copper product known as 12 alloy; duralumin; magnesium alloys of aluminum; die-casting alloys; aluminum solders.

AIRCRAFT. Lautal as a Material for Airplane Construction, P. Brenner. *Nat. Advisory Committee for Aeronautics—Tech. Notes*, no. 324; Aug. 1929, 26 pp., 12 figs.

Description of Lautal aluminum alloy without magnesium but containing some copper; production at Lauta Plant of Die Vereinigten Aluminium-Werke A.-G.; use of duralumin and Lautal bolts in detachable and non-detachable joints for airplane structures and methods of riveting, welding and testing them; wing attachments on Junkers planes; tensile tests of heat treatment and working methods; all joints of vital importance in frame should be riveted. From 1928 Yearbook of Deutsche Versuchsanstalt fuer Luftfahrt.

CORROSION. On Corona on Aluminum Conductors as Affected by Corrosion Due to Atmospheric Exposure, E. Wilson. *Faraday Soc.—Trans. (Edinburgh)*, vol. 25, no. 100, Sept. 1929, pp. 496-502, 17 figs.

Paper shows influence which corrosion has upon corona production, and critical voltage at which corona begins to develop; nature of corroded surfaces has been examined by aid of photography and X-rays, and results have been found helpful in explaining effects observed.

HEAT TREATMENT. Heat Treating Aluminum Alloys, R. J. Anderson. *Iron Age*, vol. 124, no. 9, Aug. 29, 1929, pp. 514-516.

Classification of heat-treating processes; theory of quenching and aging; principles governing annealing; high-tensile strength, ductility and hardness resulting; heat-treating equipment essential for modern aluminum alloy foundry.

TESTING. Thermo-Electric Tests for Aluminum-Manganese and Other Alloys, C. S. Taylor and J. D. Edwards. *Am. Electrochem. Soc.—Advance Paper*, no. 13, for mtg. Sept. 19-21, 1929, pp. 157-160, 1 fig.

One per cent of manganese added to aluminum has marked effect upon thermo-electric properties of metal; high thermo-electric potential of couple: alloy vs. pure aluminum forms basis of new sensitive instrument for distinguishing between pure aluminum and aluminum-manganese alloys.

ALUMINUM BRONZE

Aluminum Bronze Data. *Foundry*, vol. 57, no. 17, Sept. 1, 1929, supp. sheet nos. 779 and 780.

Causes of shots, seams and folds in aluminum bronze castings are described; disadvantages of horn gates; owing to strong drossing tendency of aluminum bronze, metal must enter mold quietly.

MANUFACTURE. The Manufacture of Aluminum Bronze, C. E. Margerum and L. H. Fawcett. *Heat Treating and Forging*, vol. 15, no. 9, Sept. 1929, pp. 1164-1166, 3 figs.

Description of methods of manufacturing aluminum bronze that are employed in United States Naval Gun Factory at Washington when using 10-in. diam. mold; shrinkage cavity confined to hot top; melting procedure, forging, and heat treatment are outlined; tables of chemical analysis and mechanical properties of forging, and of composition, heat treatment, and sclerescope measurements are given.

ALUMINUM CASTINGS

Advantages of Aluminum as a Foundry Material, G. Mortimer. *Can. Foundryman (Toronto)*, vol. 20, no. 8, Aug. 1929, pp. 12-13.

Waste material in aluminum foundries is classified and methods of reducing to minimum and disposal are given.

X-RAY ANALYSIS. X-Ray Inspection of Castings. *Elec. World*, vol. 94, no. 11, Sept. 14, 1929, p. 530, 2 figs.

Figures showing acceptable condition of homogeneity and pronounced flaws justifying rejection.

X-RAY ANALYSIS. Aluminum Foundry Makes Use of X-Ray Equipment. *Iron Age*, vol. 124, no. 7, Aug. 1929, pp. 406-409, 8 figs.

Procedure used by Aluminum Co. of America in making X-ray analysis of castings in production.

ALUMINUM-COPPER ALLOYS

Copper-aluminum Alloys. *Machy. (Lond.)*, vol. 34, no. 882, Sept. 5, 1929, pp. 714-715.

Mechanical properties and casting characteristics of alloys of copper and aluminum are discussed; overcoming difficulty associated with self-annealing; industrial applications; effect of added elements of aluminum bronze; machinability.

AUTOMOBILE MANUFACTURE

FORGING. Forging and Treating Parts for the Nash. C. Longenecker. *Heat Treating and Forging*, vol. 15, no. 9, Sept. 1929, pp. 1157-1159 and 1242, 6 figs.

Description of procedure and equipment employed in heat-treating and forging departments at Kenosha plant of Nash Motors Co.; 25 steam drop hammers, ranging in size from 1000 lbs. to 6000 lbs. and 7 board hammers of 1000 lbs. to 2000 lbs.; carburizing furnaces; small parts refined in 14 furnaces of hump type, and large parts in rotary-hearth type electric furnaces.

HEAT TREATMENT. British and American Automotive Steels, J. W. Urquhart. *Heat Treating and Forging*, vol. 15, no. 9, Sept. 1929, pp. 1172-1175.

Low critical temperature of utmost importance in crankshaft and front-axle manufacture; depth of hardness in nickel-chrome steels; hard crankshaft truing operation; seat of fractures and fiber-flow effects in crankshafts; some defects of carbon-steel springs; high carbon-steel spring and recent tests; alloy steel automobile springs; influence of tempering upon above steels.

HEAT TREATMENT. British and American Automotive Steels, J. W. Urquhart. *Heat Treating and Forging*, vol. 15, no. 8, Aug. 1929, pp. 986-990, 1 fig.

Review of practice that prevails in application of various types of steels and corresponding heat treatment for major parts of motor cars.

AUTOMOBILE PLANTS

HEAT TREATING DEPARTMENTS. Uses Universal Heat-Treating Unit, F. W. Manker. *Iron Age*, vol. 124, no. 11, Sept. 12, 1929, pp. 663-666, 5 figs.

Description of heat treating units according to operation by Packard Motor Co., Detroit; three furnaces, with pushers and pullers interconnected with time controls, forming one continuous and automatic outfit; by altering time cycles and temperatures of various units, all sizes of work, from small forgings up to large axles, can be treated interchangeably.

BRONZE

HEAT TREATMENT. Problem of Bronze Hardening (La question de la trempe du bronze), J. L. Blanic. *Arts et Métiers (Paris)*, no. 107, Aug. 1929, pp. 287-291, 7 figs.

Archeological review; opposing opinions of Geoffroy and D'Arce; modern trends and processes; comparative study of strength and hardness of various tin bronzes as function of hardening temperature.

CAR BUILDING MATERIALS

ALLOYS. New Alloys in Railway Rolling Stock, F. H. Colvin. *Am. Mach.*, vol. 71, no. 11, Sept. 12, 1929, pp. 449-450, 1 fig.

Outline of advances made in railway work by use of aluminum alloys and alloyed steels; aluminum forgings, and steel alloyed with chromium, nickel, vanadium or other metals, today are finding wider use in railway work than ever before; demands for lighter and stronger parts are helping to accelerate adoption of these materials.

CASE HARDENING

Nitride and Cyanide Hardening of Vacuum Cleaner Parts, R. G. Roshong. *Fuels and Furnaces*, vol. 1, no. 3, Sept. 1929, pp. 1393-1396 and 1408, 4 figs.

Discussion of operating procedure in cyanide and nitride hardening of vacuum cleaner parts; results obtained; precautions to be observed; description of furnace equipment employed.

CASTING, CENTRIFUGAL

Centrifugal Casting, R. E. Paine. *Army Ordnance*, vol. 10, no. 56, Sept.-Oct. 1929, pp. 117-124, 5 figs.

Important features of development and application of centrifugal casting are described and possibilities of adaptation to production of shells are suggested; brief history of development is given; tables showing properties of steels suitable for shell manufacturing and relation of ingot weight of finished shells; general outline of methods for producing shell bodies.

CASTINGS—X-RAY ANALYSIS

X-Ray Inspection of Castings, A. St. John. *Fuels and Furnaces*, vol. 1, no. 3, Sept. 1929, pp. 1371-1372 and 1407-1408.

Discussion of value of X-ray inspection in foundry, which enables foundryman to make better castings and to prove that individual castings are sound and suitable for severe working conditions.

CAST IRON

Cast Iron, J. L. Kinnell. *Domestic Eng. (Lond.)*, vol. 49, no. 8, Aug. 1929, pp. 144-149, 5 figs.

Definition, chemical composition and physical properties, defects, foundry and practice and other facts with which heating and ventilating engineers should be acquainted.

MANGANESE EFFECTS. Manganese in Cast Iron, A. L. Norbury. *Foundry Trade Jl. (Lond.)*, vol. 41, no. 676, Aug. 1929, pp. 79-83, 15 figs.

Results are given of experiments which have confirmed previous results; it was found that as manganese content of grey iron is increased from 0.0 per cent to about 0.3 per cent manganese it exerts graphitizing action on cementite; that additions of 1 per cent and upwards of manganese exerts chilling action.

CHROMIUM-NICKEL ALLOYS

The Creep of 80:20 Nickel-Chromium Alloys at High Temperatures, A. G. Lobley, *Inst. of Metals—Advance Paper (Lond.)*, no. 509, for mtg. Sept. 9-12, 1929, 20 pp., 12 figs.

Wires 0.018 in., 0.0625 in., and 0.25 in.

thick were subjected to tensile stresses of 50, 100, 200, and 400 lbs. per sq. in. at temperatures of 700 deg. and 800 deg.; measurements made daily of movements; at highest temperature there was no evidence of creep stress limit; rate of flow was found to be dependent on diameter of wire as well as other factors.

CHROMIUM-NICKEL IRON

BRITTLENESS. The Brittle Range In 18 And 8 Chromium-Nickel Iron, H. H. Lester. *Am. Soc. Steel Treating—Preprint for mtg.* Sept. 9-13, 1929, no. 10, 20 figs.

Investigation of chromium-nickel iron containing 18 per cent chromium and 8 per cent nickel made by Army Ordnance Dept.; critical point determination; series of tensile tests; microscopical examination; iron austenitic at room temperature and relatively brittle on heating to about 1300 deg. fahr.; well defined critical point at 1330 deg. fahr. on heating and at 1148 deg. fahr. on cooling; loss of ductility due to formation of ferrite crystals and to precipitation of iron or chromium carbide along atomic planes in austenite grains.

CHROMIUM-NICKEL STEEL

Austenitic Steels, A. Cauveur: *Fuels and Furnaces*, vol. 7, no. 9, Sept. 1929, pp. 1365-1366.

Discussion of great progress made in relatively recent years in investigation and application of steels made austenitic by virtue of presence of large proportions of nickel and chromium.

ELECTRIC FURNACES

ANNEALING. Electric Heat in the Annealing of Metals, A. H. Vaughn. *Heat Treating and Forging*, vol. 15, no. 7, July 1929, pp. 897-903 and 912, 17 figs.

Various requirements to be met in annealing treatments are outlined and special furnace installations designed to meet them described; alloy steel bars annealed at mills; transmission gear forgings prepared for machinery; heat conservation by counterflow of charge; automobile crankshafts, low temperature anneal; large furnace for annealing petroleum stills; furnaces for treating nonferrous metals.

Progress in Electric Furnaces for Nonferrous Metals, M. Tama. *Inst. of Metals—Advance Paper (Lond.)*, no. 510, for mtg. Sept. 9-12, 1929, 8 pp., 9 figs. partly on supp. plates.

New induction furnaces of large capacity are described; they have been developed for high melting-point alloys such as nickel-brass and phosphor-bronze; 34 electric annealing furnaces of resistor type are shown to be in successful operation in large metallurgical plant; advantages of use of electricity both for melting and annealing nonferrous metals are emphasized; recent improvements in refractory linings for melting copper alloys, devices for charging swarf into electric furnaces, and various types of electric bright annealing furnaces are described.

ARC. Electric Brass Melting, J. B. Meier. *Elec. World*, vol. 94, no. 7, Aug. 17, 1929, pp. 313-316, 3 figs.

Operation of arc furnaces in general jobbing foundry is described on basis of experience in melting 2,000,000 lb. of metals of which 40 per cent was composition, 48 per cent brass and 12 per cent high lead bearings; lower melting cost, decreased metal losses and better working conditions accompany use of electric heat.

Electric Steel Melting in Europe. *Elec. World*, vol. 94, no. 7, Aug. 17, 1929, p. 326.

Casting steel ingots at electric consumption of 210 kw.-hr. per ton with arc furnace charged with liquid metal is shown in table of electric furnace characteristics and operating data.

FOUNDRY. Electric Melting in the Steel Foundry, H. D. Phillips. *Heat Treating and Forging*, vol. 15, no. 7, July 1929, pp. 904 and 907.

Adaptability in operation, increased recoveries and control up to high melting temperatures place electric furnace as best melting unit for small foundry; early electric furnaces; operating expense.

HIGH FREQUENCY. Inductor Coils for the High-Frequency Furnace, G. N. Schuette. *Indus. and Eng. Chem.—Analytical Edition*, vol. 1, no. 3, July 15, 1929, pp. 141-144, 3 figs.

Description of furnace used for experimental work by U. S. Bureau of Mines; consists of 18-kv.-amp. high-frequency converter, including 220 to 6600-volt reactive transformer, tank of twelve condensers and mercury-to-copper electrode discharge gap operating in hydrogen.

LABORATORY. Electric Furnace for Laboratory (Horno electrico para Laboratorio), A. L. Guerrero. *Anales de Ingenieria (Bogota, Colombia)*, vol. 38, no. 430, Jan. 1929, p. 2, 4 figs. on supp. plates.

Brief description of small tubular furnace; tube of alundum or porcelain, 40 cen. long by 5 or 7 cm. diameter, on which is wound solenoid of 12 m. of chrome-nickel wire $\frac{1}{16}$ in. by 0.0275 in., with wrapping of alundum cement; consumes 600 watts with current of 110 volts.

MELTING. Development in the Utilization of Electric Heat for Electric Melting Furnace (Entwicklung der Elektrowaermeverwertung der elektrische Schmelzofen), R. Kratochwil. *Sparwirtschaft (Vienna)*, no. 1, Jan. 1929, pp. 12-16.

Electric furnaces in metal industry; various designs of induction furnaces of Roechling-Rodenhauser, Ajax-Wyatt; costs of operation.

RESISTANCE. An Improved Form of Electric Resistance Furnace, W. Rosenhain and W. E. Prytherch. *Iron and Steel of Canada (Gardenvale, Que.)*, vol. 12, no. 7, July 1929, pp. 181-182.

Electric resistance furnace is described for which advantages are claimed in regard to higher available working temperatures up to 1400 deg. cent. durability, and freedom from oxidation of carbon or graphite pellets, or short rods placed end to end in refractory sheathing tube which fits easily over them; heating occurs by contact resistance; sheathing tube prevents access of air sufficiently to avoid any appreciable burning of carbon.

Experimental Contribution to the Study of Heating and Electric Furnaces (Contribution experimentale à l'etude du chauffage

et des fours electriques), O. Dony. *Académie Royale de Belgique—Bul. de la Classe Des Sciences (Brussels)*, vol. 15, no. 4, 1929, pp. 243-253, 2 figs.

Notes on use of iron resistors up to 1200 deg. and electrothermic distillation of hydrocarbons with iron resistors.

SPECTROSCOPIC ANALYSIS. The Design and Operation of Vacuum Furnaces with Carbon Resistor Tubes, A. S. King. *Am. Electrochem. Soc.—Advance Paper*, no. 6, for mtg. Sept. 19-21, 1929, pp. 47-60, 5 figs.

Two types of electric vacuum furnaces described in full detail are result of years of study on rendering metallic vapors luminous "temperature radiation"; various spectroscopic studies are briefly described.

FURNACES

HEAT TREATING. Modern Furnaces and Their Application, R. E. Talley. *Heat Treating and Forging*, vol. 15, no. 9, Sept. 1929, pp. 1205-1207.

Importance of heating operations; modern automatic furnaces accurate; results obtained with two large automatic rotary-hearth furnaces for hardening and drawing, respectively, and with intervening quenching and handling equipment, used for heat treatment of crankshaft forgings; efficiency of rotary-hearth and pusher-type furnaces.

Pusher Type Furnaces Used in Heat Treating Forgings, W. N. Robinson. *Fuels and Furnaces*, vol. 7, no. 9, Sept. 1929, pp. 1421-1424 and 1428, 6 figs.

Furnace installation recently completed in forge shop consists of continuous type oil-fired billet-heating furnace, gas-fired, in-and-out type forging furnace, electrically-heated continuous-type hardening and tempering furnaces, and electrically-heated nitriding furnace.

GAS FIRED. Annealing Steel Sheets in Continuous Gasfired Kilns, J. B. Nealy. *Am. Soc. for Steel Treating*—TRANS., vol. 16, no. 3, Sept. 1929, pp. 429-434, 3 figs.

Increasing use of long furnaces or kilns, which are automatic and continuous in operation; for heat treating steels is resulting in progressive betterment in their design and control; description of two modern gas-fired kilns used in white and black annealing respectively is given; these are part of equipment of new plant of Youngstown Sheet and Tube Co. of East Chicago.

DESIGN. Heat Treating Furnace Design, J. H. Gumz. *West. Gas*, vol. 5, no. 8, Aug. 1929, pp. 22-23 and 48.

Influence of automobile and airplane manufacture on design of furnaces is pointed out; factors affecting design are discussed.

REFRACTORY LININGS. Improving of Refractory Lining of Heat Treating Furnaces for High Temperature Annealing of Steel Castings, W. J. Merten. *Am. Soc. Steel Treating—Preprint for mtg.*, Sept. 9-13, 1929, no. 15, 8 pp., 4 figs.

Highly refractory glazing for protective coating to be applied on ordinary firebrick furnace wall surfaces for high-temperature annealing of large section steel castings or forgings; directions for improvement of furnace linings in annealing practice in steel foundries to permit complete exploitation of potential physical characteristics of large cast steel parts by thermal refinement at high temperatures; coating steel castings for protection against excessive scaling.

TEMPERATURE CONTROL. Control for Continuous Furnaces, H. W. Moss and P. S. Austen. *Heat Treating and Forging*, vol. 15, no. 9, Sept. 1929, pp. 1201-1204 and 1211, 6 figs.

Discussion of means of close temperature regulation for mass production from continuous furnaces, including pyrometer controllers for electric furnaces and electrically operated fuel valves for gas and oil furnaces; controlling furnace zones; limits of temperature control; control for muffle-type furnace.

MELTING—DESIGN. Port Design, L. M. Wilson. *Fuel (Lond.)*, vol. 8, no. 8, Aug. 1929, pp. 380-384.

Factors affecting design of ports for melting furnaces.

METALLURGICAL—FUEL ECONOMY. Use of Temperature Heat-Content Diagrams in Metallurgical Processes (Die Anwendung des It-Diagramms auf metallurgische Prozesse), P. Rosin. *Metall und Erz (Berlin)*, vol. 36, no. 2, Jan. 2, 1929, pp. 29-36, 13 figs.

Thermodynamics of metallurgical processes; theoretical thermal efficiency and fuel consumption; effect of quality and quantity of fuel, preheating, and excess of air on efficiency of process; fuel consumption and efficiency of furnaces in practice.

TEMPERATURE DISTRIBUTION. Temperature Distribution in Combustion Furnaces, M. H. Mawhinney *Am. Soc. Mech. Engrs.—Advance Paper*, for mtg. Sept. 11-13, 1929, 5 pp., 5 figs.

Results of temperature measurements made in test furnace to determine temperature distribution in heating chamber for different temperatures and different methods of firing; majority of tests consisted in heating furnace to various temperatures and holding, or soaking, furnace at temperature for total time of eight hours; heating characteristics of under, side, and direct firing; effects of temperature in furnace, of time, furnace dimensions, and heating materials.

REFRACTORY MATERIALS. The Shape of Refractory Bricks for Suspended Roofs (Gestaltung der feuerfesten Steine fuer Haengedecken), Harraeus. *Feuerfest (Leipzig)*, vol. 5, no. 6, June 1929, pp. 102-105, 43 figs.

Author discusses factors influencing durability of refractory bricks in furnace roofs; he reproduces large number of shapes for suspended-roof bricks and criticizes various methods of suspension.

HEAT TREATMENT

Heat Treating with Precision, A. D. Dauch. *Heat Treating and Forging*, vol. 15, no. 8, Aug. 1929, pp. 1033-1036, 3 figs.

Discussion of necessity and means for assuring accuracy in heating articles in large quantities; specific pieces of equipment are detailed.

Heat Treatment Well Grounded in Experience But Not Yet a Science, J. R. Miller. *Iron Age*, vol. 124, no. 9, Aug. 29, 1929, p. 513.

Brief discussion of need for wider knowl-

edge of science of heat treating; use of X-ray as aid is pointed out.

CONTRACT. Developing a Heat-Treating Service Plant, A. M. Cox. *Heat Treating and Forging*, vol. 15, no. 8, Aug. 1929, pp. 985-986, 2 figs.

Main steps in manufacture of heat-treated steel products; savings to manufacturing plant using commercial service.

HEAT TREATMENT EQUIPMENT

Nickel Coated Pots Show Longer Life, G. R. Greenslade. *Iron Trade Rev.*, vol. 85, no. 7, Aug. 15, 1929, pp. 387-388, 3 figs.

Description of pressed steel containers for lead, salt cyanide, or caustic which are coated with non-oxidizing layer of nickel; no tendency to force two metals apart when they are heated to high temperatures; comparison of thermal conductivities of nickel-coated steel and typical alloy steel used for containers. From Inco.

Heat Treatment Equipment. *Machy. (Lond.)*, vol. 34, nos. 873, 874 and 875, July 4, 11 and 18, 1929, pp. 421-424, 457-461 and 485-489, 27 figs.

July 4: Description of multiple-unit electric, high-speed steel hardening, spring hardening and tempering, sheet-steel normalizing, hump hardening, and homo tempering furnaces. July 11: Normalizing furnace for forgings; oil-cooling apparatus; bright annealing and gas-sealed hardening furnaces July 18: Sodium cyanide hardening; cyanide hardening furnace; automatic annealing machine; electric annealing and muffle furnaces; gas flame control system. (Continuation of serial.)

METALLURGY

Principles of Metallurgy, J. L. Bray. Boston, Ginn and Co., 1929 (Engineering series), 568 pp., illus., $5.80.

Concise presentation of metallurgical practice from mining of ore to sale of refined metal; refractories, fuels and metallography are also treated, and references to further information given; should be especially useful for students of other branches of engineering who wish general survey of this subject. Eng. Soc. Lib.

Demands of Chemical Industry on Metallurgy, B. D. Saklatwalla. *Metals and Alloys*, vol. 1, no. 1, July 1929, pp. 8-13.

Relationship of chemical and metallurgical industries is pointed out; major factors affecting corrosion of metals; discussion of corrosion-resisting alloys; progress of applied metallurgy.

The International Relationship of Minerals. *Chem. Age (Lond.)*, vol. 21, no. 527, Aug. 3, 1929, pp. 9-11.

Influence of metallurgy and metals industry upon peace and war; international exchange of minerals is inevitable; mineral distribution is controlling factor in defense.

Some Methods of Research in Physical Metallurgy, W. Rosenhain. *Inst. of Metals—Advance Paper (Lond.)*, no. 509, for mtg. Sept. 9-12, 1929, 36 pp., 14 figs.

Paper describes methods which have been developed in recent years, and particularly in metallurgy department of National Physical Laboratory, for study of metals, especially in connection with determination of equilibrium diagrams; methods of determining and recording thermal curves, resistivity-temperature and dilatation-temperature curves, are discussed in detail, and brief account is given of novel form of electric dilatometer, making use of measurements of capacity of small condenser which is varied by dilatation of specimen.

STEEL

Recovery of Hyper-Tempered Steels (Sur les phenomenes lors du revenu des aciers hyper-trempes), P. Chevenard and A. Portevin. *Académie des Sciences—Comptes Rendus (Paris)*, vol. 188, no. 26, June 24, 1929, pp. 1670-1672, 2 figs.

Examples of two types of dilatometric recovery-cycle of austenitic steels in non-equilibrium state are: hyper-tempered manganese-carbon steel or sorbite, on cooling of which there is no further reaction, and hyper-tempered chromium-carbon steel in which austenite is converted by heat into less carburized form and complex iron chromium carbide, while cooling produces martensity; in both cases there is increase in hardness of about 200 Brinell.

AIRCRAFT. Special Steels, J. C. Firth. *Times Trade and Eng. Supp. (Lond.)*, vol. 24, no. 576, July 20, 1929, (Aero Sec.) p 23.

Discussion of progress made in recent years in endeavor to produce best steels for airplane use; steels developed possessing peculiar characteristics which specially adapt them for solution of different problems; molybdenum, nitriding and rust-resisting steels; cold reduction by rolling.

AMMONIA SYNTHESIS EFFECT. Study of an Iron Alloy Used in a Synthetic Ammonia Plant (Studio di una ferro lega usata in un impianto per la preparazione di ammoniaca sintetica), M. Raffo. *Metallurgia Italiana (Milan)*, vol. 21, no. 6, June 1929, pp. 213-219, 11 figs.

Investigation of causes of rupture of catalysis tubes; analyses of test pieces; micrographs of fractures; rupture in service depends upon nature of crystal structure, and on presence of cinder included in metal during manufacture of tube; heat treatment, causing migration of carbon, diminishes brittleness to some degree.

AUTOMOBILE. A Comparison of Auto Steels, J. W. Urquhart. *Blast Furnace and Steel Plant*, vol. 17, no. 8, Aug. 1929, pp. 1161-1164 and 1171, 1 fig.

Discussion of various steels used in automobile manufacture; compositions of various steel alloys and their appropriateness for chassis, engine and body parts.

BRONZE COATING. Effect of Molten Bronze on Steel, L. T. Hook. *Welding Engr.*, vol. 14, no. 7, July 1929, pp. 53-56, 9 figs.

It is shown that molten high-strength bronze applied to steel which is free from stresses will not penetrate or cause cracks.

CARBURIZED—TESTING. A New Method of Testing the Depth of Case on Carburized Steel, F. A. Firestone and E. J. Abbott. *Metals and Alloys*, vol. 1, no. 1, July 1929, p. 18, 1 fig.

Article described apparatus which was devised by authors in laboratories of Department of Engineering Research of University of Michigan for Timken Roller Bearing Co., this apparatus has not been developed be-

yond experimental form; but it offers considerable possibilities for control and testing work on case-carburized products.

ELASTIC LIMIT. Elastic Limit Steel, F. G. Marton. *West. of Scotland Iron and Steel Inst.—Jl. (Glasgow)*, vol. 36, Mar. 1929, pp. 83-91 and (discussion) 91-94, 5 figs. on supp. plates.

Kinds of elastic limit steel are discussed; results of tests of various examples are given; methods of testing are explained.

HEAT RESISTING. Heat-Proof Steels (Warmfeste Stahle), E. Houdremont and V. Ehmeke. *Kruppsche Monatshefte (Essen)*, vol. 10, July 1929, pp. 79-94, 16 figs.

Method for determination of heat-resisting properties; curve showing heat resistance relative to time; heat resistance of steels used in manufacturing valves for combustion engines; behavior of steels in temperature ranges below 650 deg., stretch limit and comparative heat-resistance curves; tabulation of test results.

MAGNET. Investigation on Dependence Between Temperature Variation and Flux-Density of Permanent-Magnet-Steels, A. F. Stogov and V. S. Messkin. *U. S. S. R. Sci.-Tech. Dept. of Supreme Council of Nat. Economy—Trans. (Moscow)*, no. 3, 1929, 41 pp., 33 figs.

Reversible and irreversible changes of magnetic flux carried out on some magnet steels which are to be used either for permanent magnets or which otherwise show good magnetic properties; investigation having taken place on bars of 200 mm. length and 1 sq. cm. cross-section; some horseshoe magnets of tungsten steel also have been investigated; test results. (In Russian with brief abstract in German.)

MAGNETIC HARDENING. The Hardening of Superhardened Steel by Magnetism, E. G. Herbert. *Iron and Steel Inst.—Advance Paper (Lond.)*, no. 5, Sept. 1929, 17 pp.

Investigation of phenomena taking place in Cloudburst process with view to their practical application in increasing hardness of work-hardened layer; endeavors to discover something of physical basis of phenomena and their relation to low-temperature changes in metal; low temperature annealing of superhardened steel; magnetic treatment arrived at by inductive reasoning from increased hardening of previously work-hardened metals as result of ageing or P-3 anneal; lattice resonance hypothesis. Bibliography.

NITROGEN CONTENT. Effect of Nitrogen in Iron and Steel, V. N. Svenchnicov. *Blast Furnace and Steel Plant*, vol. 17, no. 8, Aug. 1929, pp. 1165-1167 and 1173, 4 figs.

Investigation of source of nitrogen content in steel with particular reference to Bessemer process is reviewed; long blowing and high wind pressures.

TEMPERATURE EFFECT. Campbell Memorial Lecture on Steels at High Temperatures, A. Sauveur. *Iron Age*, vol. 124, no. 12, Sept. 19, 1929, p. 734.

Strength of steels at high temperatures is discussed; novel method of testing; significant data covering torsional strength of hot metal, number of twists before fracture (related to ductility), twisting acceleration, and "factor of stiffness" (relation between stress and strain). Abstract of paper presented before Am. Soc. for Steel Treating.

STEEL HEAT TREATMENT

Heat Treatment of Steel, H. Pennington. *Oil Weekly*, vol. 54, no. 12, Sept. 6, 1929, pp. 101-102, 104, 106, 108 and 110, 1 fig.

Cone roller and race thrust bearing of rotary swivel; taper taps; sucker rods; heat treated drill pipe; oven furnace; electric heat treating furnace; quenching bath; heating billet to forge.

Heat Treatment of Steel, H. Pennington. *Oil Weekly*, vol. 54, no. 11, Aug. 30, 1929, pp. 30, 32, 70 and 74, 5 figs.

Method of furnishing large diameter shafts with reliability and strength commensurate with size is hollow boring shaft before treating; due to heat treatment, setting up far stronger internal structure in steel; eight-inch shaft with four-inch hole in it, made of high carbon alloy steel, may then be approximately 45 per cent stronger than solid eight-inch shaft, both made of same steel analysis; process; forging qualities; molten bath furnace; pot failures; testing bits; hard surfacing. (Continuation of serial.)

A Study of Burning and Overheating of Steel, W. E. Jominy. *Am. Soc. for Steel Treating—Trans.*, vol. 16, no. 3, Sept. 1929, pp. 372-391, 17 figs.

This section covers particularly forging of steels, after heating in various atmospheres, to determine limiting temperatures in forging; these experiments were conducted on series of plain carbon and alloy steels; tests are summarized in table showing temperatures at which various steels investigated will burn if forged immediately after heating in direct-fired gas furnace when using excess of gas and air.

A Year's Progress in Steel Treating, H. F. Moore. *Iron Age*, vol. 124, no. 9, Aug. 29, 1929, pp. 517-518.

Review of progress made in case carburizing; development in heat treatment of steel rails; knowledge of heat treatment important to design; future predictions for tungsten-carbide alloy.

Heat Treatment of Steel, H. Pennington. *Oil Weekly*, vol. 54, no. 10, Aug. 23, 1929, pp. 27-29 and 114, 3 figs.

Molybdenum steels, S. A. E. 4000 series; chromium steels, S. A. E. 5000 series; vanadium steels, S. A. E. 6000 series; manganese steel; importance of drum shaft diameter; effect of mass; unequal expansion. (Continuation of serial.)

Proposed Control Methods for Small Heat Treatment Plants, W. J. Crook. *Am. Soc. for Steel Treating—Trans.*, vol. 16, no. 3, Sept. 1929, pp. 415-428, 1 fig.

Hardness testing instrument and use of furnace are shown to be adequate equipment with which small heat-treatment plant may obtain information about its raw materials and products; regenerating tests and macro-etching are discussed in relation to inspection of raw materials for ability to give results after heat treatment.

Influence of Atmospheres on the Heat Treatment of Steel, R. G. Guthrie. *Fuels and Furnaces*, vol. 7, no. 9, Sept. 1929, pp. 1345-1354, 49 figs.

Time, temperature, pressure, type of steel used and velocity and volume of given gas

over material, are all shown to be very important factors in carburization.

The Heat-Treatment of Alloy Steel, W. H. Hatfield. *Fuels and Furnaces*, vol. 7, no. 9, Sept. 1929, pp. 1355-1360.

Adequate furnaces, quenching baths, and mechanical means of efficient handling of product, accurate determination of temperature of part being treated, complete knowledge of metallography of steel being treated, time-temperature effect and speed of cooling to be made as regards influence of mass and adequate means of testing final product, are pointed out as essential aspects in heat treatment of alloy steels.

Heat Treatment of Steel, H. Pennington. *Oil Weekly*, vol. 54, nos. 8 and 9, Aug. 9 and 16, 1929, pp. 28-30 and 27-30, 4 figs.

Reasons for heat treating, objects sought and attained and value of heat treating properly selected steels for definite purposes; economic significance of steel treating. (Continuation of serial.)

Heat Treatment of Steel, H. M. Boylston. *Black and White*, vol. 2, no. 2, Sept. 1929, pp. 29-33.

Discussion of heat treatment of such structural alloy steels as molybdenum, chromium, chromium-vanadium, silico-manganese and others. (Continuation of serial.)

ANNEALING. The Hardness of Vacuum-Annealed Crystals of Iron, H. O'Neill. *Iron and Steel Inst.—Advance Paper (Lond.)*, no. 8, Sept. 1929, 27 pp., 5 figs.

Previous work on Brinell hardness and grain size of iron; construction of vacuum annealing furnace; Brinell tests on Armco tensile test piece; peculiar effect of vacuum annealing; indentation tests on aggregates and single crystals of decarburized iron; why low-carbon irons behave rather differently from decarburized iron; comparison of scratch hardness at different temperatures along various crystallographic directions of iron crystals with that of aggregate of same material. Bibliography.

OIL FUEL. Fuel Oil for Heat Treating, E. P. Kiehl. *Engrs. and Eng.*, vol. 44, no. 8, Aug. 1929, pp. 185-188, 2 figs.

Formula for determining quantity of fuel oil required; selection of oil-burning equipment; specification required of fuel oil.

PEARLITE. The Coalescence of Pearlite, J. H. Whiteley. *Iron and Steel Inst.—Advance Paper (Lond.)*, no. 11, Sept. 1929, 8 pp., 15 figs.

Transformation of gamma iron solid solution to pearlite in hypo-eutectoid occurs over small range of temperature immediately below critical point; it is shown that coalescence resulting in formation of cementite borders to pearlite takes place within this temperature range, and before all gamma iron is transformed; it is due to fact that carbide is transferred by diffusion from gamma iron to adjacent pearlite areas.

QUENCHING. Dilatation of Steel During Quenching, G. M. Eaton. *Am. Soc. Steel Treating—Reprint for mtg.*, Sept. 9-13, 1929, no. 16, 32 pp.

Theory that in heavy unmachined quenched parts passage through austenite-martensite transition produces actual incipient failure which, even if submicroscopic, cannot be healed by subsequent tempering; need for alloy steels in which quality of surface material of rolled bar is improved till it bears same ratio to core characteristics existing in carbon steels; why present endurance testing methods fail to evaluate steels; new type of dilatometer by which martensitic dilatation during quenching may be studied.

Hot Aqueous Solutions for Quenching of Steels. H. J. French and T. E. Hamill. *Am. Soc. Steel Treating—Preprint, for mtg.*, Sept. 9-13, 1929, no. 8, 30 pp., 14 figs.

Experiments relating to effect of temperature on cooling properties of liquids widely used in hardening of steels; surface and center cooling curves for small cylinders of high carbon steel quenched in water, sodium hydroxide, and sodium chloride solutions, and oils at different temperatures; possibility of using some of hot aqueous solutions to bridge gap between cooling rates obtained with water and oils at atmospheric temperatures.

STEEL MANUFACTURE

Steel Melting Practice for Large Ingots and High Grade Castings, W. H. White. *Fuels and Furnaces*, vol. 1, no. 3, Sept. 1929, pp. 1389-1392.

Discussion of melting practice in manufacture of large ingots and heavy and light high-grade castings; relation of slag to heat; pouring temperature; effects in castings; critical stages of heat; alloy steel melting.

Steel Which is Sound in Blooming, J. R. Miller. *Iron Age*, vol. 124, no. 7, Aug. 1929, pp. 399-400.

Study of causes of seams and slivers in mill rolling; precautions necessary for best results; preferential range of temperatures; high manganese content.

ELECTRIC PROCESS. Melting Practice for Three Types of Electric Steel, H. P. Rassbach. *Am. Soc. Steel Treating—Preprint, for mtg.*, Sept. 9-13, 1929, no. 12, 16 pp.

Melting practice for three types of steel made in basic electric furnace including heats for carbon tool steel, chromium-vanadium steel and high-speed steel; selection of proper scrap for each charge and savings effected; slag conditions at various stages; slag and metal analysis; importance of deoxidizing slag to a high degree; slags high in oxides may be almost completely deoxidized.

Production of Electric Steel for Castings, G. Batty. *Am. Soc. Steel Treating—Preprint for mtg.*, Sept. 9-13, 1929, no. 4, 10 pp., 1 fig.

Production of steel in acid electric furnace; two methods applicable to straight carbon and alloy steels for castings in steel foundry where scrap contaminated by adherent sand is used as part of charge; definite boil of bath must be secured, with some inevitable elimination of carbon; to "kill-off" final traces of free and active oxide of iron in bath with ferrosilicon, is neither sound nor desirable practice; pin hole problem and that of low ductilities.

TOOL STEEL PROPERTIES

The Properties of Various Tool Steels, A. R. Page. *Heat Treating and Forging*, vol. 15, no. 7, July 1929, pp. 843-845.

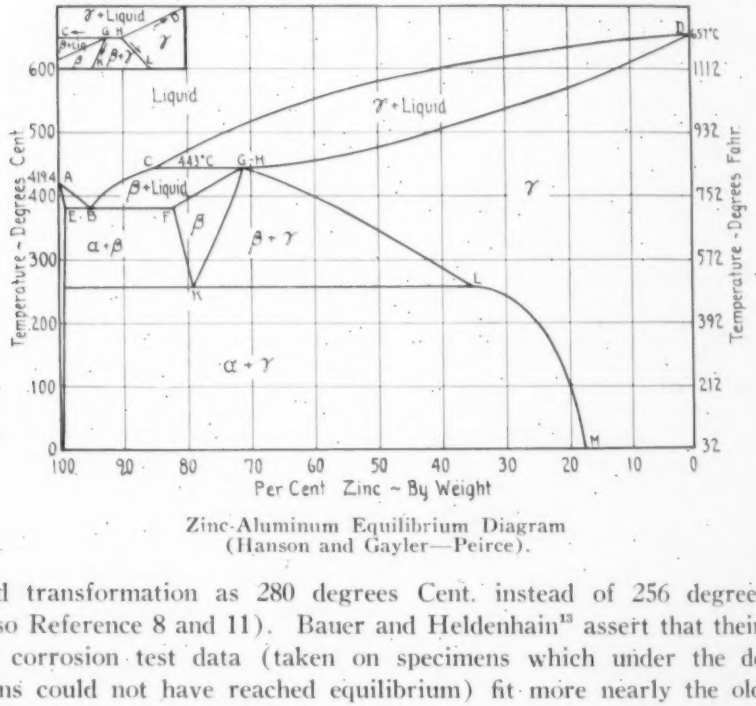
Recommended Practice Committee Releases*

CONSTITUTION OF ZINC-ALUMINUM ALLOYS

By E. A. Anderson†

The equilibrium diagram of the zinc-aluminum system has been the subject of much research, but due to the slow rate at which equilibrium is attained in alloys of this group, the real complexity of the system was not realized in the early studies.[7 to 8]

The most widely accepted diagram is that determined by Hanson and Gayler.[10] This diagram should be modified in the zinc solid solution region to include the work of Peirce.[9] Tanabe[11] and Isihara[12] confirm Hanson and Gayler's work on all essential points. Isihara[10] and Jares[17] would place the



Zinc-Aluminum Equilibrium Diagram
(Hanson and Gayler—Peirce).

eutectoid transformation as 280 degrees Cent. instead of 256 degrees Cent. (See also Reference 8 and 11). Bauer and Heldenhain[13] assert that their physical and corrosion test data (taken on specimens which under the described conditions could not have reached equilibrium) fit more nearly the older diagram of Rosenhain and Archbutt.[6]

The diagram given here is that of Hanson and Gayler[10] altered in the alpha region by Peirce's[9] findings. The solubility of aluminum in zinc (alpha

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solid solution) extends to about 0.85 per cent of aluminum at 335 degrees Cent., decreasing to about 0.25 per cent of aluminum at room temperature. Zinc is soluble in aluminum to about 70 per cent at 443 degrees Cent., decreasing to about 18 per cent at room temperature.

The inset in the upper left hand corner of the diagram represents the supposed conditions existing at points G and H of the main diagram. G is the peritectic point being the composition of the solid formed by the reaction of liquid of composition C with solid of composition H. Tanabe[11] gives the composition at the point G as 30.0 per cent of aluminum and at H as 30.5 per cent of aluminum.

The structure of the intermediate constituent β formed by this peritectic reaction has not been published. It is unstable below 256 degrees Cent., and its decomposition into the α and γ solid solutions results in spontaneous evolution of heat. All alloys of this system containing 0.25 to about 81 per cent of aluminum are characterized by age hardening phenomena.

Crystal structure at room temperature as determined by X-ray methods indicates[15] that α occurs as an hexagonal close-packed arrangement of atoms of the same dimensions as the zinc lattice. In other words, the preliminary evidence indicates that the presence of up to 0.8 per cent of aluminum does not measurably distort the zinc structure. γ assumes the face-centered cubic lattice of aluminum modified from 4.0435 Ångstrom units (pure aluminum) to 4.0345 Ångstrom units for the saturated solid solution. Mixtures of α and γ give the two patterns superimposed.

References

[1]Kozo Miyazaki, Science Reports, Tohoku Imperial University, Vol. 17, Series 1, p. 877-81.

[2]H. Gautier, *Bulletin* de la Societe d'Encouragment pour l' Industrie Nationals, 1896, p. 1293-1318, p. 1307.

[3]Heycock and Neville, *Journal* of the Chemical Society, 1897, Vol. 71, p. 383-422.

[4]Shepherd, *Journal* of Physical Chemistry, 1905, Vol. 9, p. 504-12.

[5]Ewen and Turner, *Journal* of the Institute of Metals, 1910, Vol. 4, p. 128-58.

[6]Rosenhain and Archbutt, *Transactions* of the Royal Society, 1912, Vol. 211-A, p. 315-43.

[7]Eger, Internationale Zeitschrift für Metallographie, 1913, Vol. 4, p. 29-128.

[8]Bauer and Vogel, Mitteilungen aus dem königlichen Materialprüfungsamt zu Berlin-Lichterfelde West, 1915, Vol. 33, p. 146-98.

[9]Peirce, *Transactions* of the American Institute of Mining and Metallurgical Engineers, 1923, Vol. 68, p. 767-95.

[10]Hanson and Gaylor, *Journal* of the Institute of Metals, 1922, Vol. 27, p. 267-94.

[11]Tanabe, *Journal* of the Institute of Metals, 1924, Vol. 32, p. 415-52.

[12]Isihara, *Journal* of the Institute of Metals, 1925, Vol. 33, p. 73-89.

[13]Bauer and Heldenhain, Zeitschrift für Metallkunde, 1924, Vol. 16, p. 221-8.

[14]Nishimura, Memoirs of the College of Engineering of Kyoto Imperial University, 1924, Vol. 3, p. 133-63.

[15]Phebus and Blake, *Physical Review*, 1925. Series 2, Vol. 25, p. 107.

[16]Isihara, Science Reports, Tohoku Imperial University, 1926, Vol. 15, Series 1, p. 209-24.

[17]Jares, *Proceedings* of the Institute of Metals Division of the American Institute of Mining and Metallurgical Engineers, 1927, p. 65-79.

[18]C. Benedicks and H. Löfquist, International Congress for Testing Materials, 1927, Part 1, p. 265-90.

CONSTITUTION OF IRON-SULPHUR ALLOYS

By G. F. Comstock*

The elements iron and sulphur form a compound FeS which contains 36.5

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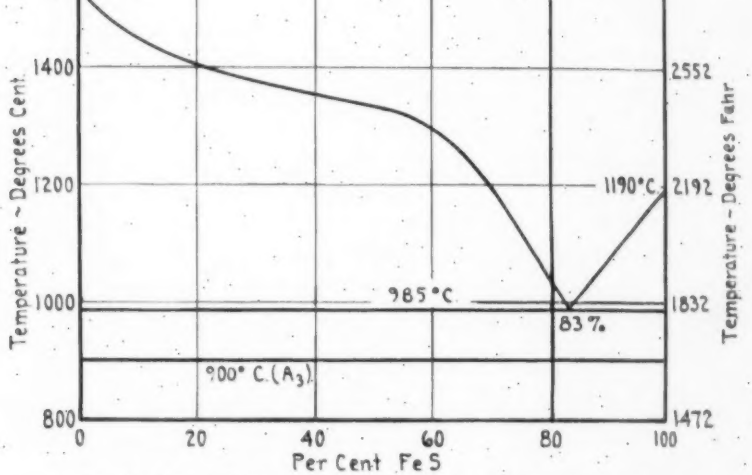
per cent sulphur. Since for practical consideration in the metallurgy or metallography of iron and steel it is unnecessary to deal with alloys of higher sulphur content, this discussion will be confined to the alloys of iron and iron sulphide (FeS).

Nearly all authorities seem to be agreed that the system Fe-FeS is a simple eutectiferous one, and there is fairly general agreement in regard to the complete miscibility in the molten state. The equilibrium diagram has been determined by Friedrich,[1] by Loebe and Becker,[2] and more recently by Kozo Miyazaki,[3] who took special precautions to avoid contamination by oxide.



Constitutional Diagram for Iron-Sulphur Alloys (Miyazaki).

These diagrams agree closely. Starting with the freezing point of pure iron at 1530 degrees Cent., the liquidus descends in an irregular curve to the eutectic at 985 degrees Cent., then rises to the freezing point of FeS at 1190 degrees Cent. The form of the liquidus curve may be reproduced quite closely with the following data, taken from Miyazaki's paper:

With 20.9 per cent FeS, the liquidus is at 1404 degrees Cent., with 61.34 per cent FeS, it is at 1295 degrees Cent.; the eutectic contains 83 per cent FeS; and with 98.63 per cent FeS the liquidus is at 1183 degrees Cent.

The shape of the liquidus curve given by Benedicks and Lofquist is similar, but they show the eutectic to contain 31.3 per cent sulphur, or 86 per cent FeS, as nearly as it could be measured from their diagram. Sauveur[4] states that this eutectic contains 85 per cent FeS and melts at 950 degrees Cent. McCance has given the eutectic temperature as 980 degrees Cent. Friedrich showed the eutectic to contain 85 per cent FeS and to melt at 983 degrees Cent., and the melting point of FeS at 1171 degrees Cent. Shibata found the melting point of FeS to be 1163 degrees Cent. within 4 degrees plus or minus,[5] instead of 1190 degrees Cent., according to Benedicks and Lofquist. However, these values are in fair agreement and probably Miyazaki's determinations can be accepted as practically correct.

In regard to the solubility of sulphur or FeS in solid iron, the informa-

tion available is not very definite. By electrical resistance measurements Miyazaki showed that the solubility must be less than 0.5 per cent FeS, and from microscopic observations, he concluded that it was "practically zero at ordinary temperature." Benedicks and Lofquist state that "the solubility of sulphur in solid iron may be estimated at about 0.015 to 0.020 per cent sulphur," and Wohrman agrees that only about 0.05 per cent FeS is held in solid solution by pure iron at atmospheric temperature. Some investigators seem to have found a slight lowering of the critical points of iron due to the presence of sulphur, but in general this effect has been inappreciable.

Iron sulphide (FeS) is easily recognized in polished sections of iron or steel by its bright yellow color, and its property of being readily attacked by boiling alkaline sodium picrate. Cementite, also darkened by this reagent, is much harder and paler in color, and could hardly be confused with the sulphide. The Fe-FeS eutectic structure has not been observed with the microscope, probably because (according to Wohrman) the components coagulate very readily in the presence of excess iron.

The presence of carbon and manganese, as in commercial steels and cast iron, or of oxygen as in ingot iron, has of course an important influence on the equilibrium relations of iron and sulphur. These ternary alloys, however, are not included in the present discussion.

References

[1]Shown by Wohrman, TRANSACTIONS, American Society for Steel Treating, Vol. 14, p. 274, 1928.
[2]Shown by Benedicks and Lofquist, International Congress for Testing Materials, Part I, p. 265, 1927.
[3]Kozo Miyazaki, Science Reports, Tohoku Imperial University, Series I, Vol. XVII, p. 877.
[4]Sauveur's Metallography and Heat Treatment of Iron and Steel, Third Edition, 1926.
[5]Kinzoku no Kenkyu, Vol. 3, p. 403.

PHYSICAL CONSTANTS OF ZINC

By E. A. Anderson*

Atomic Weight, Atomic Number, Electrochemical Equivalent, Color—Zinc has an atomic weight of 65.38 and occupies the thirtieth position in the periodic system of the elements. Its electrochemical equivalent is given in the Smithsonian Physical Tables as 1.2194 grams per ampere hour. Zinc is a bluish-white metal.

Crystal Structure—The fundamental crystal unit of zinc is an hexagonal, close-packed arrangement of atoms in which the axial ratio has been determined as 1.86 by X-ray methods and by goniometric measurements of crystal faces. The nearest distance between atoms in the basal plane was found by Peirce, Anderson and Van Dyck[1] to be 2.657 Ångstrom units and in the pyramid plane 2.903 Ångstrom units. These results confirm Hull's excellent work.[2]

Allotropy of Zinc—While a number of workers have claimed the ex-

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istence of one or more allotropic modifications of the zinc lattice on the basis of variations in certain properties at definite temperatures, recent investigations carried on simultaneously by Peirce, Anderson and Van Dyck[4] and the Bureau of Standards[3] failed to reveal any change in the type of crystal structure in pure zinc, at atmospheric pressure, in the temperature range between 20 and 400 degrees Cent.

Simon and Vohsen[4] have recently published data on X-ray studies of zinc and cadmium at different temperatures. No evidence of any change in crystal structure with temperature was found.

Melting Point—The melting point of zinc, 99.94 per cent pure, has been determined as 419.4 degrees Cent. On a zinc in which no impurities could be detected in a 16-inch quartz spectroscope, the melting point has been found to be 419.45 degrees Cent.

Boiling Point and Vapor Pressure—C. G. Maier,[5] working in the Bureau of Mines, has developed from the most recent work on the vapor pressure of zinc the following formula for this value:

$$\text{Log. } P = 12.0013 - \frac{6670}{T} - 1.1265 \times \text{log. } T$$

P = pressure in mm. of mercury
T = absolute temperature

This reference also places the boiling point of zinc at 905 ± degrees Cent. at 760 mm. pressure.

Latent Heats of Fusion and Vaporization, Specific Heat—From these same data Maier concludes that the latent heat of fusion at 419.4 degrees Cent. is 26.6 gram calories per gram. The latent heat of vaporization at 905 degrees Cent. is 426.8 gram calories per gram.

Wüst's[6] data on the specific heat of zinc have been widely accepted. Eastman, Williams and Young[7] report values in good agreement. Wüst's data follow:

Temperature, Degrees Cent.	0	100	200	300	400
Specific Heat	0.0875	0.0965	0.1052	0.1139	0.1226

Specific Gravity—The specific gravity of zinc varies somewhat with the composition and physical state of the specimen. For a cast zinc 99.94 per cent pure, the Bureau of Standards[3] has recently obtained a value of 7.131 at 25 degrees Cent. On rolled zinc of the same order of purity values ranging from 7.135 to 7.150 have been recorded, the value 7.142 being an average figure.

Pascal and Jouniaux[8] found the specific gravity of molten zinc to be 6.92 at the melting point; 6.81 at 600 degrees Cent. and 6.57 at 800 degrees Cent. The value at the melting point has been independently checked and confirmed.*

Electrical Conductivity—The electrical conductivity of zinc varies with the composition and the rolling treatment, being highest in hot rolled, 99.94 per cent zinc. Zinc of this purity has a specific conductivity of 16.40 × 10⁶

*Unpublished data—New Jersey Zinc Company.

Mhos (28.27 per cent with copper as 100 per cent) at 20 degrees Cent. when cold rolled as compared with 16.50×10^4 Mhos (28.44 per cent) when hot rolled. A zinc containing 1.1 per cent of lead and 0.05 per cent of cadmium has specific conductivities of 16.28×10^4 Mhos (28.06 per cent) and 16.34×10^4 Mhos (28.17 per cent) respectively for the two rolling conditions.*

Thermal Conductivities—The Smithsonian Physical Tables give the following values for the thermal conductivity of zinc at three temperatures:

Temperature Degrees Cent.	Thermal conductivity-calories per square centimeter per centimeter per second per degree
—160	0.278
18	0.2653
100	0.2619

While no reference is made as to the purity of the zinc or the form in which it was tested, the data probably represent a pure zinc, i. e., 99.9+ per cent pure, in the cast condition.

Hugh M. Brown[9] has recently published data on the effects of magnetic fields on the thermal conductivity of zinc. A value of 0.281 calories per square centimeter per second per degree is reported for cast zinc at 0 degrees Cent. A longitudinal field of 10,000 gauss produced no change in this value.

Coefficient of Expansion—The International Critical Tables give the following data on thermal expansion:

Temperature Degrees Cent.	Linear Coefficient of Expansion
—170° to 60°	29.5×10^{-6} per degree C.
0° to 300°	35.4×10^{-6} per degree C.

The coefficient of cubical expansion is given in the Smithsonian Physical Tables as 89.28×10^{-6} per degree Cent. between 0 and 100 degrees Cent.

The following data* are available for hot rolled zinc (99.94 per cent pure) in the range 20 to 40 degrees Cent.:

Direction Tested	Linear Coefficient of Expansion
With Grain	0.0000325 per degree C.
With Grain	0.000014 per degree F.
Across Grain	0.000023 per degree C.
Across Grain	0.0000098 per degree F.

Transmission of Sound—The velocity of sound in zinc has been determined by Masson[10] as 3,700 meters per second (16,140 feet per second). The velocity of sound in air is 332 meters per second. While no specific statement is made, the above data probably refer to cast zinc at room temperature.

Optical Properties—The reflection of light rays from zinc is, of course, a function of the condition of the surface of the specimen. Provostaye and Desains[11] state that 68 per cent of normally incident white light is reflected by zinc. Drude[12] found that 77 per cent of red light is reflected. In neither case is the condition of the surface specified.

The Smithsonian Physical Tables state that the total radiation from an oxidized zinc surface is 0.110 as compared with a black body at 1.00.

W. W. Coblentz[13] found that the reflectivity of a polished zinc surface

*Unpublished data—New Jersey Zinc Company.

goes through a minimum at 1.0 Ångstrom units, rising again at 2.0 Ångstrom units.

Surface Tension—The surface tension of zinc in air was found by Quinke[14] to be 967.4 dynes per centimeter. The capillary constant (a^2) is given as 28.6 mm. Between 580 and 630 degrees Cent. the surface tension changes to 707.5 dynes per centimeter and the capillary constant to 25.54 mm.

T. R. Hogness[15] gives $d = 758 - .090\ (T-419)$ for the surface tension of zinc at T degrees Cent.

Magnetic Susceptibility—McLennan, Ruedy and Cohen[16] studied the magnetic susceptibility of zinc single crystals with the following results:

Parallel to hexagonal axis $= 190 \times 10^{-6}$
Perpendicular to hexagonal axis $= 145 \times 10^{-6}$

Mechanical Properties*—The mechanical properties of zinc vary with the composition and the physical state of the specimen. Cast zinc will vary between 6,000 and 16,000 pounds per square inch in tensile strength, depending upon the grain size. In the rolled condition the tensile strength will vary from 14,000 pounds per square inch for a pure zinc in the hot rolled condition to 35,000 pounds per square inch for a hard rolled prime western zinc. The scleroscope hardness will vary between 11 and 25 under these conditions.

The Brinell hardness** of cast zinc varies with the grain size and composition of the specimen. Values ranging from 30 for a coarse grained high grade zinc to 60 for a fine grained prime western zinc have been recorded.

The Brinell test is of little value for testing rolled zinc less than one-eighth inch thick. On heavier gauges, the values range from 40 for hot rolled zinc (99.94 per cent pure) to 60 for cold rolled prime western zinc.

References

[1]W. M. Peirce, E. A. Anderson and P. Van Dyck, *Journal* of the Franklin Institute, 1925, Vol. 200, p. 349-61.

[2]A. W. Hull, *Physical Review*, 1921, Series 2, Vol. 17, p. 571-88.

[3]Bureau of Standards Scientific Paper 522, 1926.

[4]F. Simon and F. Vohsen, *Zeitschrift für Physikalische Chemie*, 1928, Vol. 133, p. 165-87.

[5]C. G. Maier, *Journal* of the American Chemical Society, 1926, Vol. 48, p. 356-64.

[6]F. Wüst, A. Meuthen and H. Durrer, *Stahl und Eisen*, 1918, Vol. 38, p. 777-81.

[7]E. D. Eastman, A. M. Williams and I. F. Young, *Journal* of the American Chemical Society, 1924, Vol. 46, p. 1178-83.

[8]P. Pascal and A. Jouniaux, *Comptes Rendus*, 1914, Vol. 158, p. 414-16.

[9]H. M. Brown, *Physical Review*, 1928, Series 2, Vol. 32, p. 508.

[10]A. Masson, Poggendorffs Annalen der Physik, 1858, Vol. 103, p. 272.

[11]F. de la Provostaye and P. Desains, *Annales de Chimie et de Physique*, 1850, Vol. 30, p. 431-43.

[12]P. Drude, *Wiedemanns Annalen*, 1890, Vol. 39, p. 481-554.

[13]W. W. Coblentz, Bureau of Standards Scientific Paper 379, 1920.

[14]G. Quinke, *Poggendorffs Annalen der Physik*, 1868, Vol. 135, p. 621-46.

[15]T. R. Hogness, *Journal* of the American Chemical Society, 1921, Vol. 43, p. 1621-8.

[16]J. C. McLennan, R. Ruedy and E. Cohen, *Proceedings* of the Royal Society, 1928, Vol. 121, p. 9-21.

*Unpublished data—New Jersey Zinc Company.

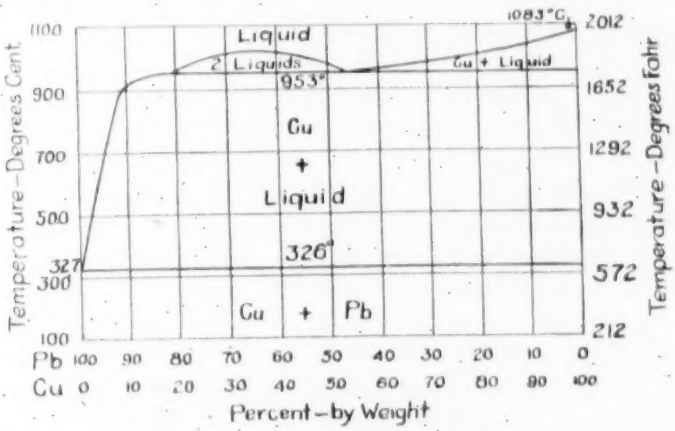
**10 mm. ball, 500 kg. load, 30 seconds duration of load.

CONSTITUTION OF COPPER-LEAD ALLOYS

By G. C. Holder*

Copper and lead are partially miscible in the liquid state, and completely immiscible in the solid state. The constitution of this system has been investigated by Roberts-Austen; Heycock and Neville; Hiorns; Friedrich and Leroux; Giolitti and Marantonio; Friedrich and Waehlert; and Bogitch.

The eutectic alloy contains 0.06 per cent copper and has a freezing point only slightly more than 1 degree Cent. below that of lead, 327 degrees Cent. According to Friedrich and Waehlert, the temperature of the monotectic reaction



Copper-Lead Equilibrium Diagram.

or the horizontal portion of the liquidus curve is at 953 degrees Cent. and the two conjugate liquid solutions contain about 19 and 54 per cent copper, respectively. The two liquid layers reach the same concentration at a temperature slightly in excess of 1000 degrees Cent. Alloys between 100 and 54 per cent copper form homogeneous solutions above the liquidus curve. As soon as the temperature falls to the liquidus, crystals of copper separate from the mother liquor and continue to do this until a concentration of 54 per cent copper is reached. Further abstraction of heat causes the second liquid layer to form as the crystallization of copper continues. Because of the presence of three phases in contact with each other this stage of the crystallization process takes place at a constant temperature of 953 degrees Cent., and when the first liquid phase (54 per cent copper) is exhausted only the second phase (19 per cent copper) remains with the frozen copper. The temperature then falls with further separation of copper until the eutectic point at 326 degrees Cent. is reached, when final solidification occurs. Freezing of alloys of less than eutectic concentration proceeds normally. At no point is there any evidence of solid solubility, in spite of the similarity of crystal structure (face centered cubic) of the two component metals.

With a moderate rate of cooling, alloys containing less than 15 per cent lead have a fairly uniform lead distribution. Chilled alloys of less than 30 per cent lead are fairly uniform. In appearance, such alloys are reddish gray.

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News of the Society

THE following letter addressed to W. H. Eisenman, secretary of the A. S. S. T., should be of considerable interest to executives in planning the technical convention activities of their men. Feeling that this letter outlines a very workable plan for selecting men to attend certain conventions this letter is published in full and with the author's permission. Although the letter was received the 26th of September it was too late for publication in the Convention Number of TRANSACTIONS October, 1929. The letter is as follows:

"Dear Sir:

"Feeling that the plan which the International Harvester Company has adopted as regards their representation at the A. S. S. T. Conference and Steel Exhibition may be of interest, I am pleased to hand you a brief outline of the activities of our group, and the reasons for such procedure.

"Sending representatives to conventions has become more or less a habit, and in many cases is productive of but little good to either the men who attend or the company who send them.

"The International Harvester Company, however, realized the possibilities of organized representation at such conferences and exhibitions, and Mr. A. A. Jones, our Manager of Manufacturing, adopted the plan of sending the Metallurgists as a group, made up of one man from the Metallurgical Staff of each Harvester Works (this year 12 men attended).

"The plan calls for a definite program for each day, and the group's activities are so directed that papers of special interest are covered, and certain equipments are studied and reported on.

"Each morning is given over to the discussion of certain subjects and problems of the various Harvester Works, such as Methods and Standards, Steel Specifications, and Heat Treating and Forging Equipment.

"In order that the exhibition may be thoroughly canvassed, each man is given a list of equipment and accessories and each morning they report on their findings; this keeps the group informed of what is being shown, and where to go to get such information as he may desire without the loss of a lot of time aimlessly walking around. The technical papers are covered in a similar way and any paper having valuable and interesting data are noted for future reading in the TRANSACTIONS, if the men make certain notes from hearing the reading of the papers and discussions they are given out at our morning meetings and discussed there.

"If our program calls for matters dealing with the manufacture of steel or special furnaces or testing equipment, some representative from a steel manufacturer, or the manufacturer of the testing equipment, is invited to sit in at the meeting, which gives the men the benefit of their knowledge and is helpful in getting correct data on the subjects. The group attendance at Philadelphia and Cleveland was quite successful and few things of interest were overlooked.

"This annual gathering of these men with a definite program, as related above, has resulted in a closer relationship and co-operation, and a better understanding of each Works problems, combined with the many benefits derived from discussions of technical papers, the search for new and improved equipment, material, etc., including numerous chats with men who are an authority on Metallurgy and Steel manufacture.

"Each man has to report in full his attendance at the convention, covering his observations and the discussions of the group meetings, as it may affect the individual Works he is connected with, and the International Harvester Company as a whole. These reports are directed to this office and are circulated to the general office and to all Works and interested parties.

"This office also has a check-up system on these reports in order that we may know if the suggestions as recommended are followed up and carried out.

"We believe that only through a concentrated and directed effort can a convention of the magnitude of the A. S. S. T. be properly covered and the greatest good derived from contact with it.

"It may also be of further interest to know that the Company arranges for a Harvester group dinner for some evening during the week, when some man of note is invited to be our guest and speaker. At Cleveland we had Mr. W. P. Woodside, one of the founders of the Society, and Mr. F. P. Gilligan, Past President. The men appreciated greatly the remarks offered by both Mr. Woodside and Mr. Gilligan and they were a real inspiration to the group in the furtherance of their work.

Yours very truly,

J. E. Robinson, Supervisor of Metallurgy.
International Harvester Company,
606 South Michigan Ave., Chicago."

ENGINEERING EXTENSION DIVISION

John F. Keller of Purdue University is again with the society for a period of six months, and is just completing his six-lecture course on "Steel and Its Treatment," offered by the society, in co-operation with Purdue University, and the chapters in the communities of Albany, Schenectady, Syracuse, Rochester and Buffalo.

A second series of lectures will commence on Monday, November 4, with five classes in and near Pittsburgh. Through the hearty support of the Pittsburgh Chapter, these classes should be very well attended.

With the splendid co-operation of the chapters, the first series of classes for this year set a new high record as the largest enrollment in any of the six series of classes that have been held over the past three years. This enrollment is most gratifying.

The enrollment was as follows: Albany 81, Schenectady 382, Syracuse 188, Rochester 164, and Buffalo 228 a total of 1,043. An outstanding enrollment was that of the General Electric Co. of Schenectady, from which there were 372 men.

Synopsis of Engineering Extension Course

"Steel and Its Treatment," the course of six lectures given by Professor Keller, is addressed especially to men in the metal fabricating and processing fields who have not been trained in the fundamental principles that underlie the behavior of iron and steel when worked mechanically or when heat treated. The language used throughout is non-technical, and many of the complexities of iron and steel are illustrated by ingenious demonstration apparatus and by lantern slides and the blackboard. A synopsis of each lecture is given below.

Lecture No. 1. The manufacture of iron and steel from the crude method of rule of thumb to present highly efficient method of procedure control. Methods of selecting metals and identification, including a brief description of the "Spark Test."

Lecture No. 2. A practical demonstration of the "Spark Method" of selecting iron and steel on a live emery wheel. The basic principles of forging, with emphasis on the cause of defects, and the effect of heat and work upon the crystalline structure of iron and steel.

Lecture No. 3. Annealing, its purpose and importance in mass production of today, particularly in machining qualities. The refining of the crystalline structure to develop the physical characteristics desired in metal. The importance of annealing iron and low carbon welded parts such as chains, bolts, and other machine parts. The Iron-Carbon diagram explained.

Lecture No. 4. Solid solution theory illustrated through a colored Iron-Carbon diagram. The decalescence and recalescence points clearly illustrated and demonstrated by an electric device that clearly visualizes these phenomena and their importance in the hardening of tool steel and the heat treating of machinery parts to develop the physical characteristics desired. The carburizing of steel and its heat treatment.

Lecture No. 5. Quenching media, their function in the retention of characteristics desired in steel. Tempering (drawing) of tool steel and the tempering of machinery parts to develop toughness and fatigue-resistance qualities to such tools or parts. The heat treatment of high speed and alloy steels. A brief outline of metallography with lantern slides showing photomicrographs of the important microconstituents of steel when properly and improperly heat treated.

Lecture No. 6. Why iron and steel warps and cracks in the various operations of heating and cooling. This phase of the subject is also touched upon from the foundry angle, i. e., the warpage of castings in their cooling operation and from the effect of oxyacetylene and other autogeneous methods of welding. Why certain types of welds fail.

Sufficient time is given at each meeting to discuss individual problems that may be of general interest to the group.

Semi-annual meeting of the society will be held in New York City, February 7 and 8, 1930. Hotel Pennsylvania will be headquarters.